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A PRELIMINARY EVALUATION OF THE ENVIRONMENTAL SAFETY ASPECTS OF NUCLEAR ROCKET FLIGHT OPERATION (U)

January 1963

Nuclear Utility Services, Inc.
Washington, D. C.

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NUCLEAR REACTORS FOR ROCKET PROPULSION (M-3679, 28th. Ed.)

A PRELIMINARY EVALUATION OF THE ENVIRONMENTAL SAFETY ASPECTS OF NUCLEAR ROCKET FLIGHT OPERATIONS (U)

For

Space Nuclear Propulsion Office
Atomic Energy Commission
National Aeronautics and Space Administration

Contract SNPC-6

By

Nuclear Utility Services, Inc.

January, 1963

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ACKNOWLEDGMENTS

This evaluation has been prepared at an early stage in the development of NERVA and Saturn. Although such a study should be made at this stage, designs are not yet firm. Many development and research programs are under way and information is only beginning to become available from experiments and analyses by many people in many organizations. The design, construction, testing and launching of a nuclear rocket engine introduces concepts and problems which were not thought of only a few years ago. There are many facets of the program which bear upon safety and the understanding of the interrelations has been accomplished by relatively few people.

It has been necessary for the authors to contact the organizations with tasks relating to safety so as to integrate these efforts into this evaluation of the potential effect on the environment. These organizations and their staffs have been most courteous and helpful in providing information about their programs and assisting in evaluating their impact on safety. Colonel Ralph S. Decker, Safety Officer, and George P. Dix, Project Technical Director, of the SNPO Safety Office and Arnold B. Joseph, Environmental and Sanitary Engineering Branch, DRD, have arranged for the procurement of documents and liaison with the various organizations. Many individuals have contributed to this effort. The following have been especially helpful: at LASL, L. D. P. King and W. R. Stratton; at NVPO-MSFC, J. Malcolm Rives; at WANL, W. H. Esselman, W.H. Arnold and A. Boitax; and at Cape Canaveral, Majors R. Hock and J. Rawers.

In the NUS organization the members of the staff who have made major contributions to this study are Raphael S. Daniels, Luis F. Garcia and Jack C. Scarborough.

Morton I. Goldman
Manager, Nuclear Safeguards

C. Rogers McCullough
Vice President, Development

January, 1963

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I. INTRODUCTION

This report deals with an evaluation of the environmental hazards associated with nuclear rocket flight operations initiated from Cape Canaveral, Florida. The effort was broken into six tasks: I - The collection, review, and evaluation of existing information on the source and environmental conditions; II - The evaluation of the hazard from radioactive and toxic materials as related to their transport through the environment; III - Consideration of radiation standards applicable to this effort; IV - Evaluation of the sensitivity of the models to the parameters describing source and environmental conditions; V - The recommendation of additional research and development work to provide data required for more accurate evaluation of hazards; and VI - The suggestion of countermeasures which might be undertaken to minimize the hazards.

The study was based on the information available realizing that in many cases it was incomplete. The study indicates the potential effect of information yet to be obtained -- and the importance of additional studies.

A study of this sort is highly important at this time since it shows those areas needing additional study, design changes that should be made, and additional safeguards that should be provided, at a stage where these efforts will cause the minimum disruption of the program.

As a basis for this study, it is assumed that the nuclear reactor is not to be operated until the vehicle impact point has passed beyond the Blake Escarpment. The problem, therefore, resolves itself into two phases: the radioactivity which might be released to the environment from the time that the reactor arrives on the launch site until it reaches the Blake Escarpment; and the amount of radioactivity released beyond the Blake Escarpment upon its final disposal. On the basis of these assumptions, the radioactive material which might be released during the first phase can only result from an accidental nuclear excursion. Such an excursion might be caused by a number of malfunctions which will be discussed in the body of the report. Without an accident which results in a nuclear excursion, there will be no radioactive material entering the environment during the first phase of the nuclear rocket flight. Subsequent to the operation of the reactor, there will

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be fission products in the reactor core. Any nuclear excursion subsequent to this period would add a certain additional amount of radioactive material to that already present, the total of which is available to enter the environment.

Since the nuclear and mechanical design of the NERVA engine has not yet been decided, it is not possible to make precise quantitative estimates of either the amount of radioactivity which might be released or the conditions bringing this about. Likewise, there are requirements for additional data on the effect of explosive destruct mechanisms and particularly the amount of burnup which will be possible on re-entry of the reactor into the earth's atmosphere. Nevertheless, sufficient data exists in our opinion to give adequate bounds to the problem by making a preliminary estimate and to indicate directions of efforts for filling in the necessary gaps as required. This will be discussed in more detail in the body of the report.

Historically, reactor hazard evaluation has not included an evaluation of accident probabilities. Those accidents for which credibility exists have been analyzed and evaluated, and safeguards incorporated to mitigate the credibility or resulting hazards of those with high damage potential. Those which are considered incredible are ignored. This approach has also been used in this evaluation, although the novelty of the nuclear rocket program puts a much greater strain on the decision of credibility or incredibility.

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II. DESCRIPTION OF THE ENVIRONMENT

A. CAPE CANAVERAL AREA

1. Geography

The Cape Canaveral Missile Test Annex (CCMTA) is located in Brevard County along the Atlantic Ocean in Central Florida. Cape Canaveral is the most conspicuous projection of land on an otherwise smooth eastern coastline of the state, about 200 miles north of Miami, 140 miles south of Jacksonville and about 50 miles east of Orlando (see Figures II-1 and II-2). The facilities are located on the barrier island area off the mainland coast, and presently consist of Cape Canaveral and a portion of Merritt Island and the northern beach area. Land is being acquired by NASA on Merritt Island and added to the present CCMTA. The boundaries within the next few years will be as shown in Figure II-3.

Complex 39 is the facility at which it is assumed nuclear rocket flights will be assembled and launched. The Complex shown in a layout drawing in Figure II-4 will consist of three launch pads about 9,000 feet apart, a vertical assembly building (VAB) for vehicle assembly, a nuclear assembly building, arming tower and canal for barge delivery of chemical vehicle stages. A crawler roadway[1] will be provided to permit transport of assembled vehicles, umbilical tower and launch rack from the assembly building to the launch pads (Figure II-5). The northernmost launch pad (Pad A) is presently designated as the site for RIFT launches.

2. Topography and Physical Features[2]

Brevard County (Figure II-2) has been classified as part of the coastal lowlands physiographic unit. Principal physical features are: the Saint Johns River Valley, the Atlantic Coastal Ridge, and the barrier islands area.

a. St. Johns River Valley

In the Saint Johns River Valley, most of the land immediately adjacent to the river is marshland ranging in width from less

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FLORIDA– COUNTIES, PLACES OF 25,000 OR MORE, AND STANDARD METROPOLITAN STATISTICAL AREAS (16)

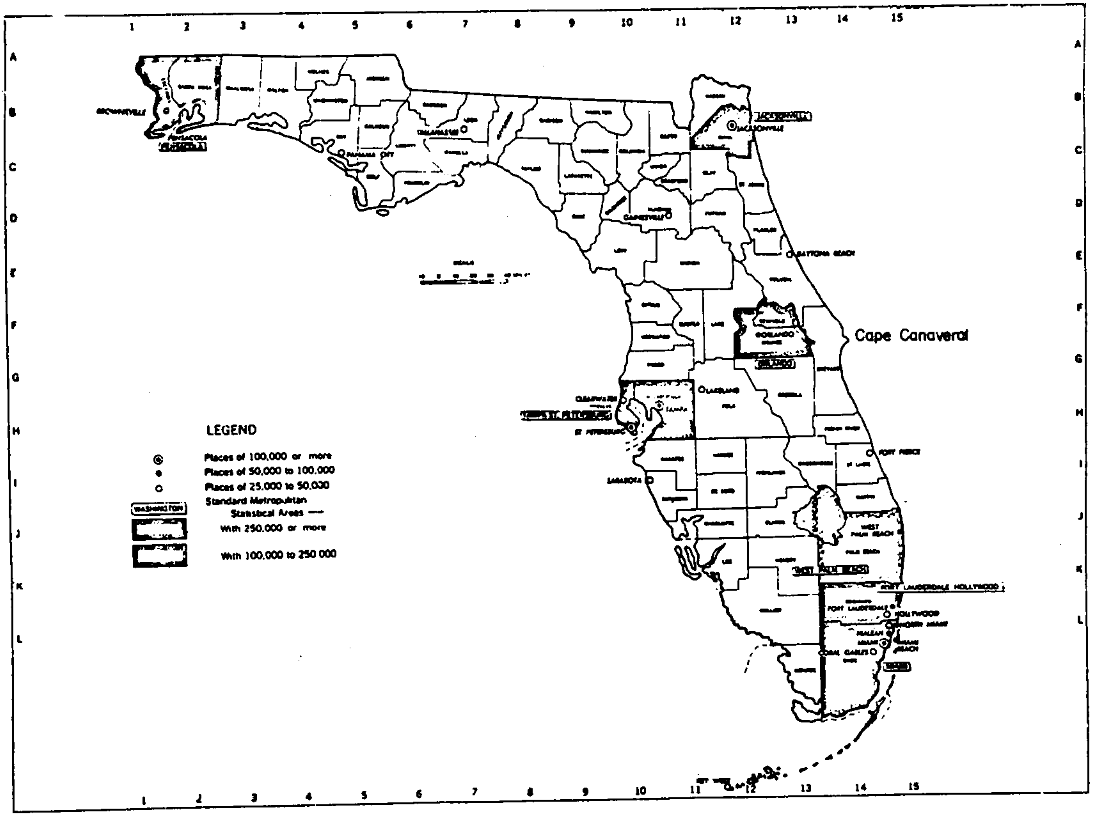

Figure II-1

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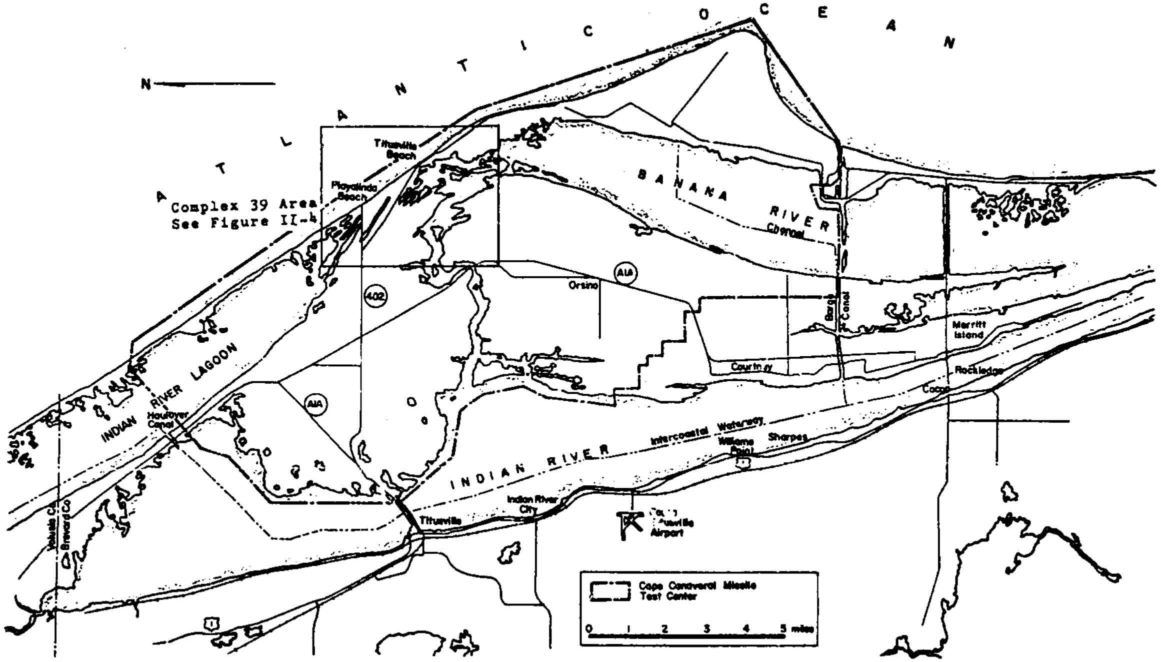
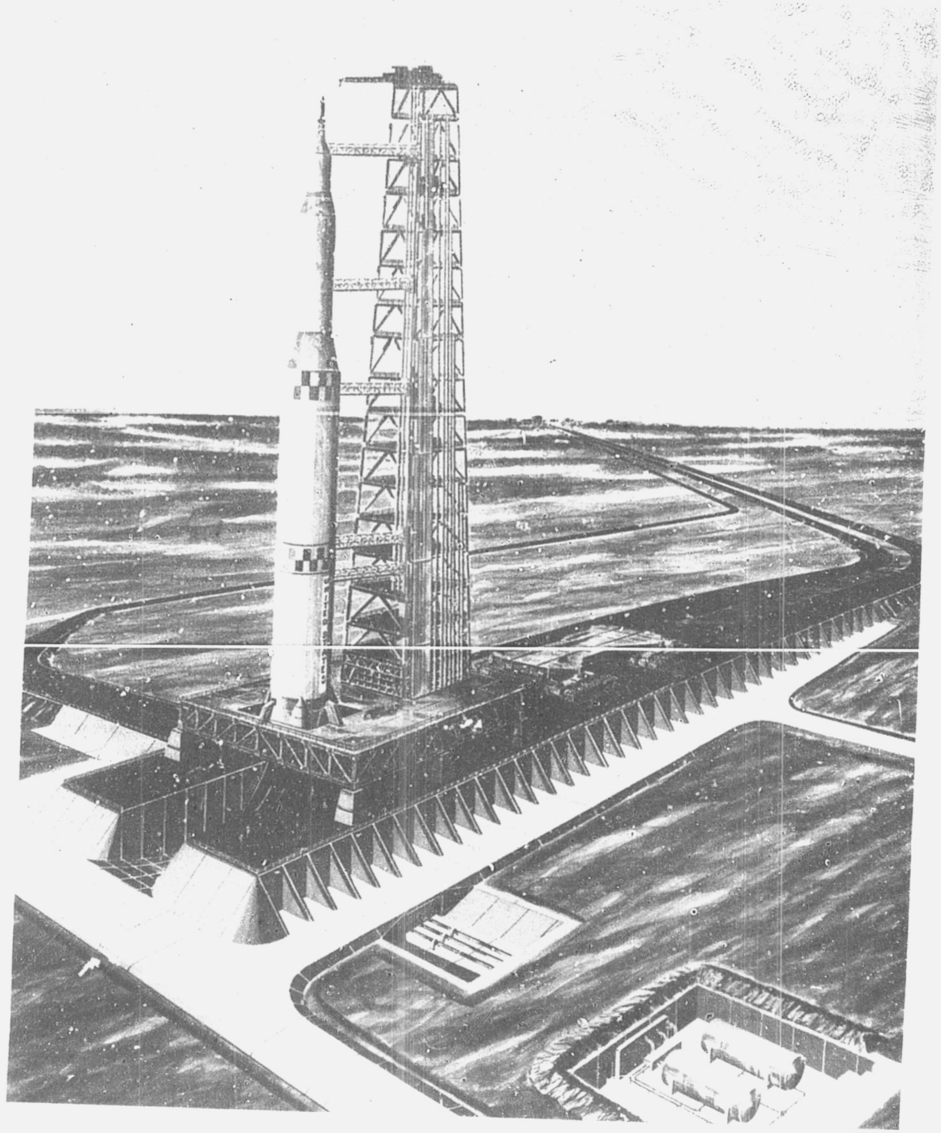

A T L A N T I C O C E A N
N
Complex 39 Area
See Figure II-4
Titusville Beach
Playalinda Beach
B A N A N A R I V E R
Channel
Orsino
A1A
402
Barge Canal
Merritt Island
Courtenay
Rockledge
Cocoa
INDIAN RIVER LAGOON
Haulover Canal
I N D I A N R I V E R
Intercoastal Waterway
Williams Point
Sharpes
Titusville
Indian River City
Airport
Volusia Co.
Brevard Co.
Cape Canaveral Missile Test Center
0 1 2 3 4 5 miles

Figure II-3

Figure II-5
Launch Pad - Complex 39[1]



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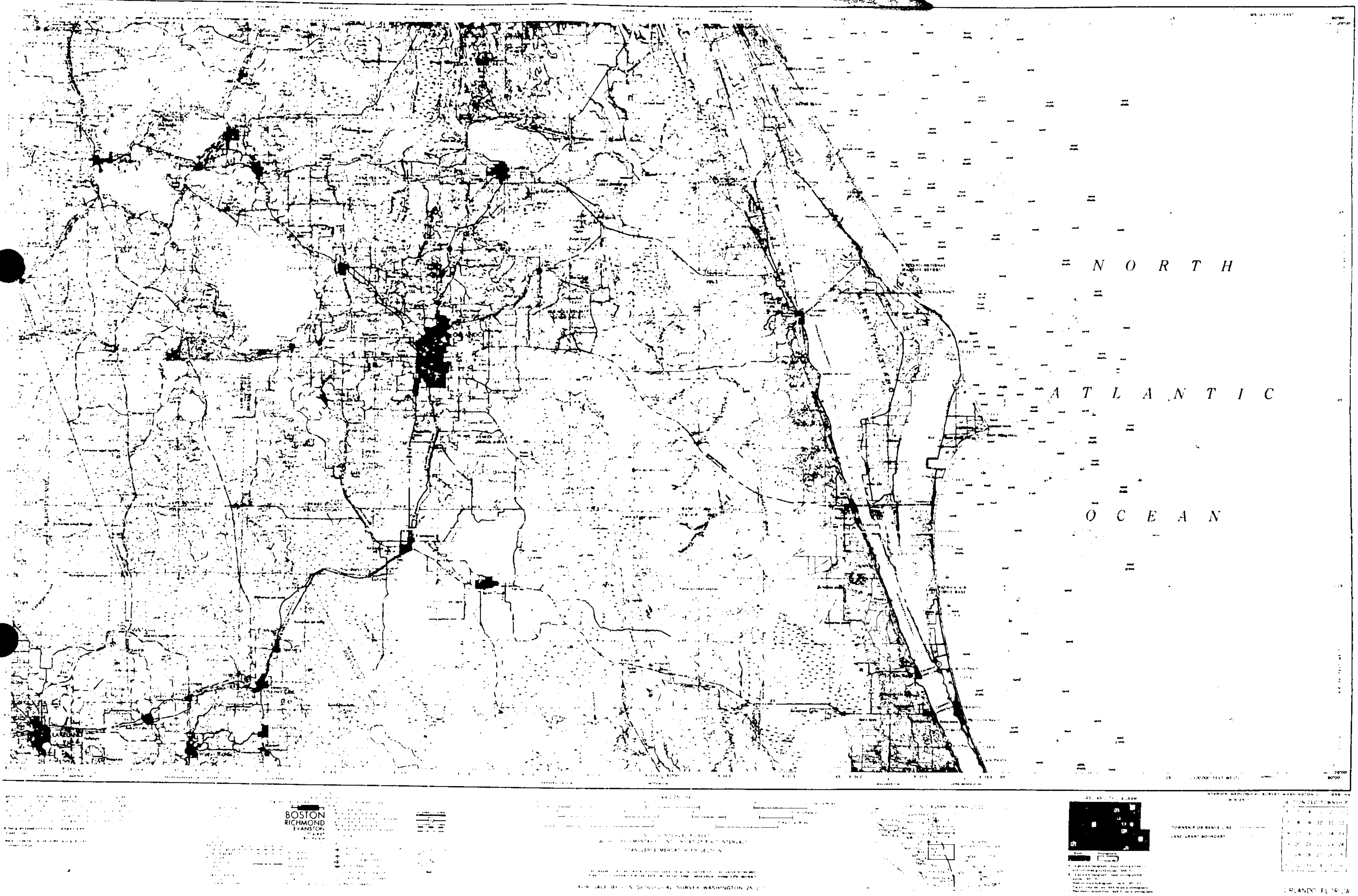

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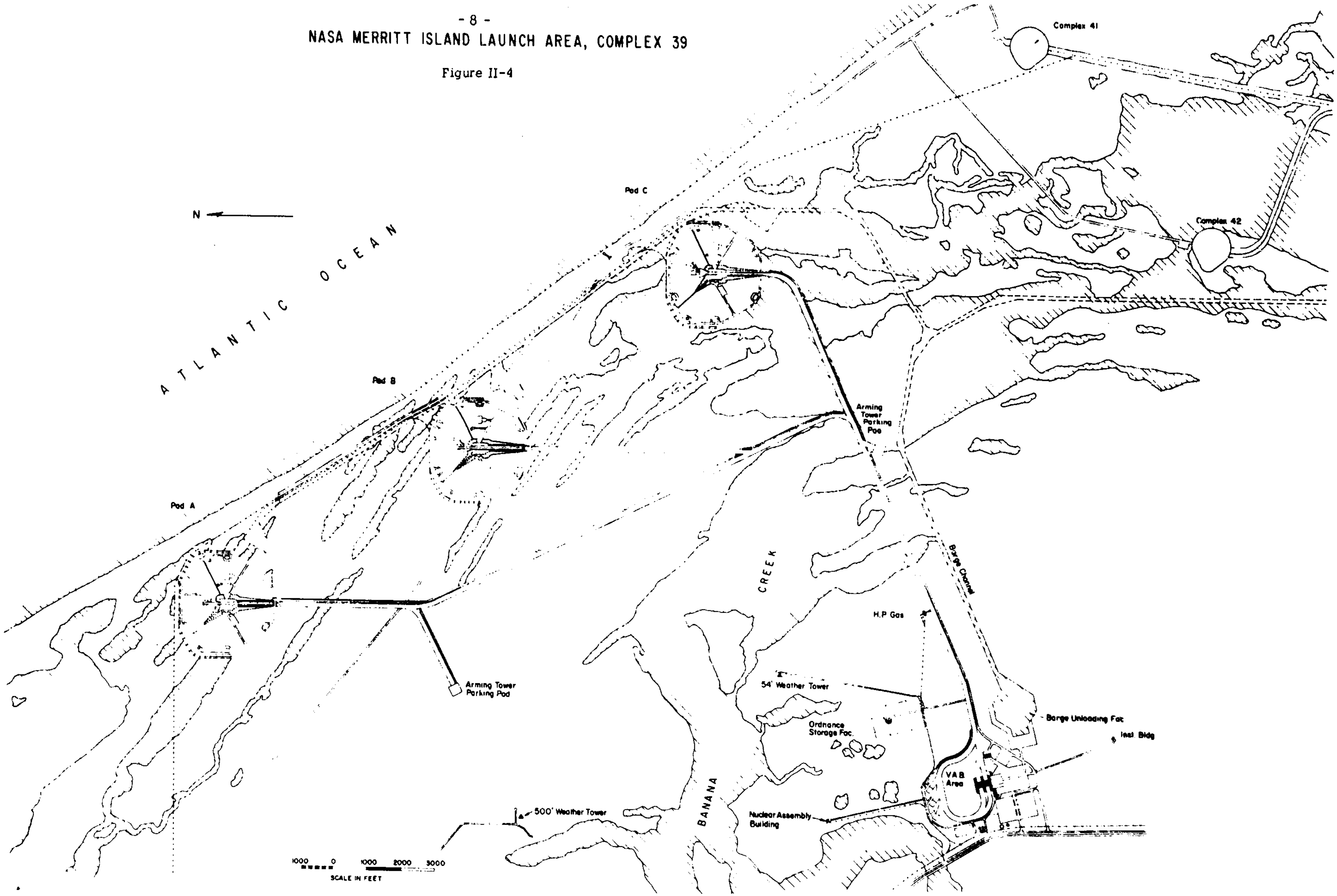
NASA MERRITT ISLAND LAUNCH AREA, COMPLEX 39

Figure II-4



than 1 mile to more than 7 miles. Those parts of the land adjacent to the river and higher than 20 feet above sea level are not generally marshy. The vegetation in the marshland consists primarily of marsh grasses and occasional hammocks or clusters of cyprus trees.

A sandy prairie zone or dry prairie zone forms the upland border of the marshland. It is several miles wide in some areas and completely absent in others. The prairie zone is part of the flood plain of the Saint Johns River and is frequently flooded. The vegetation of the zone consists principally of grasses, saw palmetto, many other low shrubs, and occasional hammocks of cabbage palm trees. A pine flatwoods forest in Brevard County lies between the prairie zone and coastal ridge. The combined width of the prairie and forest areas ranges from less than 1 mile to more than 12 miles. Where the sandy prairie zone is absent, the pine flatwoods forest borders the marshland. The forest area is relatively flat, poorly drained, and there are numerous scattered intermittent ponds, creeks, and sloughs. The altitude of the forest ranges from a few feet above sea level along the marshland border to about 35 feet above sea level along the coastal ridge border. The vegetation consists mostly of pine, saw palmetto, and wire grasses. The area is suitable for lumbering and cattle grazing.

b. Atlantic Coastal Ridge

The Atlantic Coastal Ridge in Brevard County is bordered on the west by the pine flatwoods forest of the Saint Johns River Valley, and on the east by the Indian River. The ridge ranges in east-west width from 1 1/2 to 3 miles and is continuous along the full north-south length of the County. This area has a mature dune-type topography with parallel north-south elongate ridges and intervening swales. The swales contain many shallow ponds, lakes and long and narrow sloughs. The coastal ridge ranges in altitude from sea level to 55 feet above sea level and it is the highest area east of the Saint Johns River valley. The crest of the ridge forms the natural drainage divide between the Saint Johns and Indian River basins. A series of small streams flow out of the coastal ridge and east into the Indian River. The western slope of the coastal ridge is drained by a series of small interconnecting depressions that channel water westward into the Saint Johns River. The principal types of vegetation found on the coastal ridge are saw palmetto, sand pine, scrub oak, and shrubs.

c. Barrier Islands

The barrier islands area is separated from the mainland by the Indian River and is bordered on the east by the Atlantic ocean. These islands are composed of relict beach ridges formed by the action of wind and waves of the ocean. Merritt Island, one of the barrier islands, has a maximum east-west width of about 7 miles and a north-south length of about 31 miles and is bordered on the west by the Indian River, on the south and east by the Banana River and on the north by Banana Creek. The land surface is undulating, the troughs are near sea level, and the ridges are generally not more than 10 feet above sea level. The troughs and ridges, produced during deposition, generally parallel the present coast line.

The geological development of Merritt Island was rather complex, but in general the deposition progressed from west to east. As Merritt Island formed, erosional forces tended to smooth out the ridges. Consequently, the original wavy surface of the western side has been reduced to a nearly level plain. The range in altitude in the crests and troughs of the land surface becomes greater from west to east. The surface drainage is primarily internal, being trapped in long, narrow lakes, ponds, and sloughs that have formed in the troughs. Some of these water bodies, however, have outlets to external drainage. The vegetation on Merritt Island is a mixture of the types found in the pine flatwoods forest and the coastal ridge of the mainland.

The remainder of the barrier islands is a system of beach ridges that generally parallel the present shore line. These islands separate the Atlantic Ocean from the Indian River, the Indian River Lagoon and the Banana River. They are continuous along the full north-south length of the county and generally range in east-west width from a few hundred feet to a mile. However, at Cape Canaveral, the barrier island is about 4 1/2 miles wide. The land surface of these barrier islands ranges in altitude from sea level along the shore line to

20 feet above sea level along the crest of the dune ridges. Vegetation on these barrier islands consists only of plants that can grow in relatively saline soil and air. The most common of these are sea oats, saw palmetto, sea grapes, cocoa plums, wax myrtles, lantanas, and bay cedars.

3. Geology and Ground Water Hydrology[2]

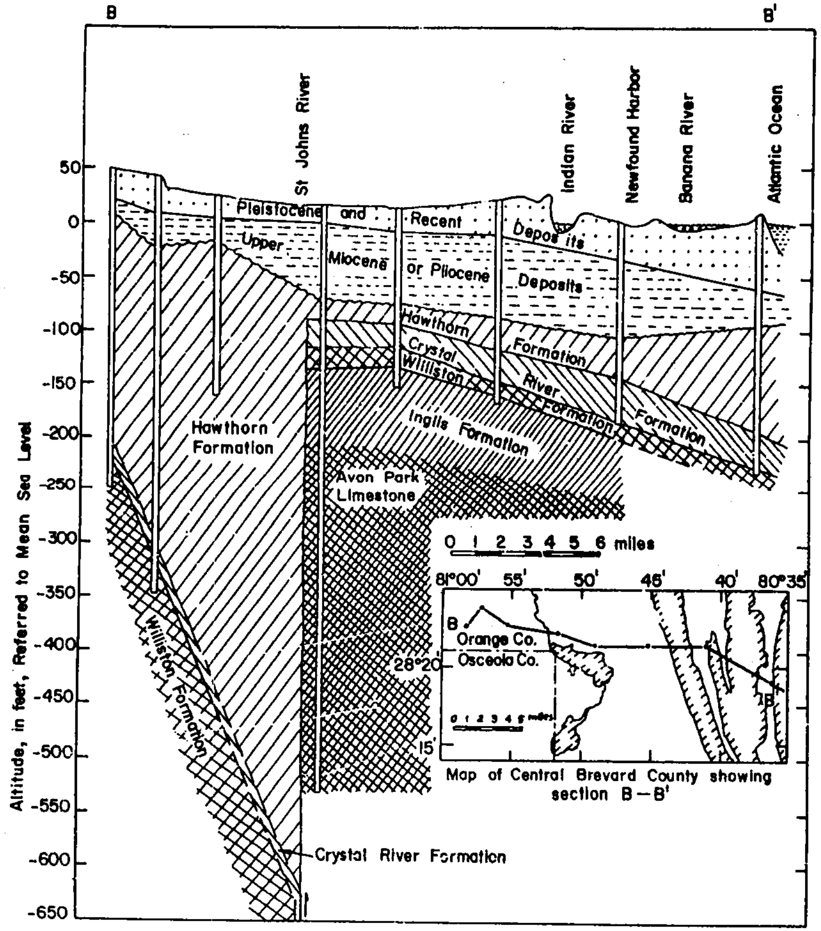
A geologic section of central Brevard County through Cocoa and Cocoa Beach is shown in Figure II-6. The county is underlaid by a series of limestone formations having a total thickness of several thousand feet. The upper several hundred feet constitute the tapped portion of the Floridan aquifer which generally includes the Avon Park limestone and the overlying Ocala group of limestone formations, all of Eocene Age. Overlying the artesian aquifer are beds of sandy clay, shells and clays of the Hawthorn Formation of Early and Middle Miocene Age and deposits of late Miocene or Pliocene Age. These beds serve to confine water under pressure in the underlying artesian aquifer. The confined beds are overlain by unconsolidated deposits of sand and sandy conquina of Pleistocene and Recent Age which completely blanket the entire County.

Ground water in Brevard County occurs under both unconfined conditions (nonartesian aquifer) and confined conditions (artesian aquifer). Generalized hydrologic conditions are shown in Figure II-7.

The nonartesian aquifer is composed of Pleistocene and Recent deposits and is exposed at the land surface. These sediments average about 50 feet in thickness in the coastal ridge but are less than 20 feet thick in the vicinity of the Saint Johns River. Nonartesian water saturates about 40 feet of the sediments in the coastal ridge area and the zone of saturation thins toward the Saint Johns and Indian Rivers. The lower part of the sediments contain salty water in some places. Upward movement of water from the artesian aquifer can occur in areas where the water table is below the piezometric surface, including areas where the water table is, or in the future may be, lowered by large withdrawals of ground water from the nonartesian aquifer. It should be noted that in some cases the artesian water contains appreciable quantities of salt.

Figure II-6

GEOLOGIC SECTION
OF CENTRAL BREVARD COUNTY (2)



GENERALIZED HYDROLOGIC CONDITIONS IN EAST-CENTRAL FLORIDA (2)

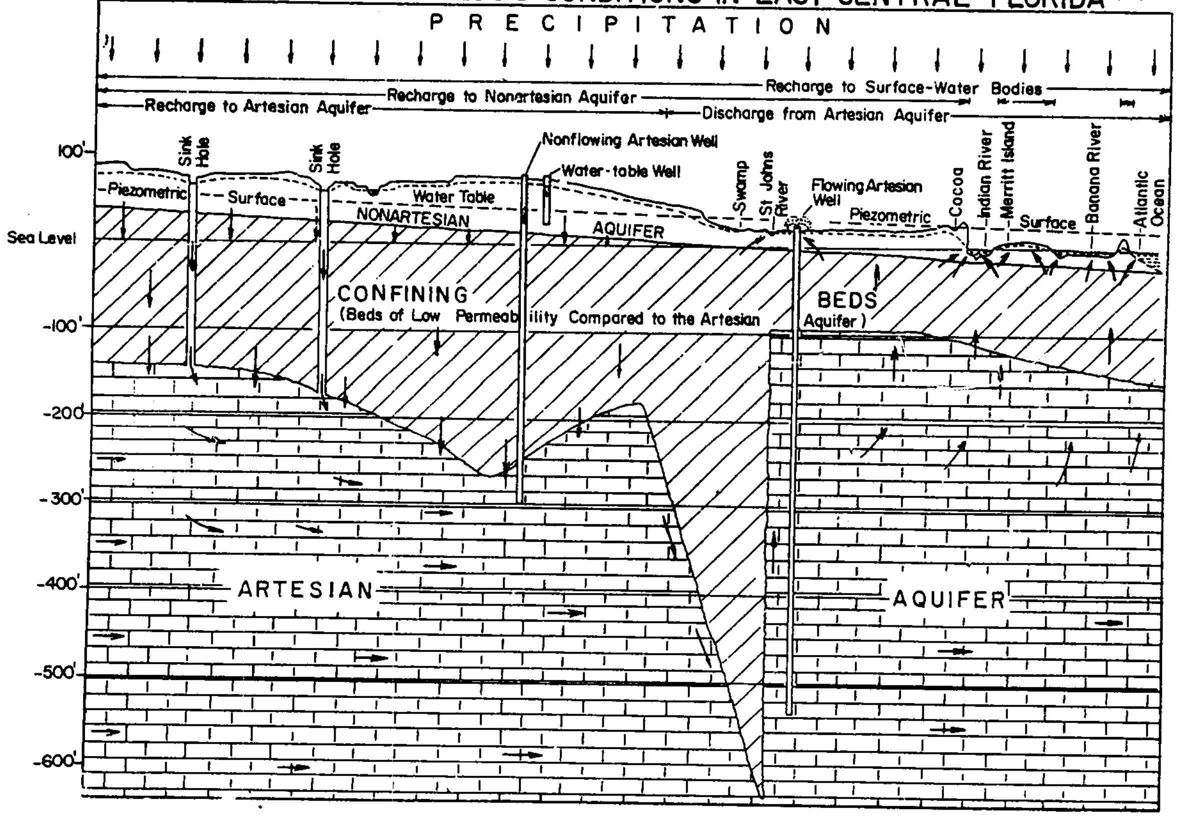


Figure II-7

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In the sandy coastal ridge area, nearly all the rainfall will enter the soil during or immediately after dry seasons. During the wet seasons the rainfall rate exceeds the infiltration rate and the surplus water drains off. In the low-lying swampy areas, very little rainfall enters the soil because the aquifer is nearly full. In the barrier islands area where the soil is very sandy, a large part of the rainfall soaks into the ground. Although part of this water is returned to the atmosphere by evaporation and transpiration, most of it seeps downward to the zone of saturation. Water in the zone of saturation moves laterally toward the ocean or river. On the mainland, flow is generally east and west from the water table divide which is parallel to and 0.5 to 1.5 miles west of the Indian River.

The source of the largest supply of ground water in Brevard County is the Floridan aquifer composed of limestone formations containing sandy and fossil-bearing inclusions. The top of the aquifer is about 75 feet below sea level in the northwestern part of the County and more than 300 feet below sea level in the south-eastern part. Artesian water under the mainland portion of the County flows northeastward, except in the area south of Melbourne where it flows almost directly east. On Merritt Island and the other barrier islands, it flows northwestward in the area north of Cocoa Beach; northeastward in the area between Cocoa Beach and Melbourne, and directly east in the area south of Melbourne. The piezometric surface of the artesian aquifer is higher than the land surface over most of Brevard County and hence most wells drilled into the aquifer will overflow at the surface.

This aquifer receives much of its recharge from the central part of the Florida peninsula, with a piezometric dome centered in Polk county about 75 miles southwest of Cape Canaveral. An area of local recharge has been identified in the Atlantic Coastal Ridge north of Indian River City, largely on the basis of the chemical quality of the water, and the relationship of water levels in the artesian and nonartesian aquifers. A comparison of the piezometric contours and the water table in the Mims area showed the water table to be some 12 feet higher than the piezometric surface. Thus, fresh water from the nonartesian aquifer moves downward into the artesian zone, reducing the concentration of dissolved ions.

The concentration of mineral ions in artesian water within Brevard County derives primarily from residual saline waters in the artesian aquifer, and generally exceeds the maxima recommended for domestic or industrial use. Moderate to high concentrations of silica, sodium, chloride, sulfate and calcium are indicated by analysis to be present in most of these waters and hence limit their usefulness. In the local recharge area in the northern part of the county, water from the artesian aquifer would be suitable for public and industrial supplies.

4. Surface Water Hydrology[2]

As described in the preceeding section, surface waters are plentiful in the Cape Canaveral area. Aside from the ocean itself, these include the mainland streams and lakes, and the Indian River Basin, the latter considered to include the many sloughs and marshes in the Merritt Island area. The Indian River is the site of a significant sport fishing activity; the mainland streams and lakes are fished and may, in the future, be used as sources of municipal water supply as discussed in Section 6-c below; the coastal waters in the area are heavily fished both commercially and for sport as described in Section 6-c.

a. Indian River Basin

The Indian River is a lagoon rather than a stream. The Brevard County section of this lagoon, including the part called Banana River, covers 235 square miles and receives the drainage from 838 square miles of the surrounding land area. Assuming an average depth of 6 feet for this lagoon, a volume of about 900,000 acre-feet, or about 3×10^{11} gallons is estimated. The Indian River is separated from the Atlantic Ocean by a long, narrow island ranging from a few hundred feet to a few thousand feet in width except near Cocoa where it widens to form Cape Canaveral. This section of the Indian River has only one direct connection to the ocean, Sebastian Inlet. It has two indirect connections: at the northern end, the indirect connection is through Haulover Canal to the Indian River Lagoon and thence through Ponce de Leon inlet to the Atlantic; southward, the connection is through the Fort Pierce inlet at Fort Pierce.

A number of small streams on the east slope of the coastal ridge flow into the Indian River. In practically every case the natural flow of these streams has been increased by connecting the upper reaches to ponds and sloughs on top of the coastal ridge. The natural flow has been increased tremendously in those that now receive runoff from the diked areas west of the ridge. These creeks in Brevard County including Sebastian Creek now carry to the Indian River the excess water from about 240 square miles of land that formerly drained to the Saint Johns River. The discharge of these small streams which are tributary to the Indian River has been gaged. The minimum discharge of these tributaries into the Indian River during the period of measurement reported was 96.5 cubic feet per second in March, 1956; the maximum, over 7,000 cfs in October of 1956. Since gaging was done at intervals of several months, no continuous record is available, but the average discharge into the Indian River appears to be in the vicinity of several hundred cubic feet per second.

Fluctuations in the level of the Indian River are relatively small. At Titusville from September, 1951, to September, 1957, the highest stage that occurred was 2.32 feet above mean sea level. The lowest stage that occurred during the same period was 0.78 feet below mean sea level. Because of the large surface area, wind causes considerable short-term fluctuation. Strong winds blowing in a north-south direction may produce as much as 2 feet of rise at one end of the river with a concurrent lowering at the opposite end. Rains produce rapid rises in the river, the amount of rise depending upon the density and areal extent of the rain. Storm rains during the middle of October, 1956, averaged about 12 inches over the entire river area in a 2-day period and produced a 12-inch rise in the river.

Salinity in the Indian River is highly variable and ranged at Titusville (during the 1953-1957 period) from 5,000 to 20,000 ppm of chloride. In the Banana River over the same period (1953-1957) the range was from approximately 7,500 to 17,000 ppm of chloride. Thus, as part of the route of radioactivity to man, these waters are only of importance in the fish population they support, since desalinization would be required to render these waters potable.

The nature of bottom sediments and their affinity for dissolved radionuclides have not been established. These could play a significant role in reducing the concentration of any radioactive materials released to the waters of the Indian River basin.

b. Mainland Streams and Lakes

The Saint Johns River forms part of the western boundary of the County, flowing northward through a wide, shallow valley. The river basin contains numerous lakes, of which several have a large storage capacity which could play a role in the use of these waters in this area. However, their use has been impeded by saltwater contamination from the surface drainage of high-chloride artesian waters used for irrigation during dry seasons.

Information on past and proposed uses of these waters for domestic supplies and for fishing is presented below in Section 6-c.

c. Coastal Ocean Waters

Coastal waters off Cape Canaveral may be divided into regions conveniently characterized by different depths to ocean bottom. For proper orientation, the assumed launch azimuth of 100° is plotted in Figure II-8 on a hydrographic chart of the downrange area. Out to depths of about 60 feet (about 15 miles downrange), shoals dominate the underwater topography. Figure II-9 is a section through the first 16 nautical miles downrange from the launch site which shows Ohio Shoal about 12 miles off-shore. The bottom continues seaward at about the same slope out to about 30 miles where the bank slopes down to depths of 2,400 to 3,000 feet to the Blake Plateau (see Figure II-10). The Blake Plateau extends out to about 200 nautical miles to the Blake Escarpment which is the name given to the Continental Slope in these waters. Figure II-11 depicts the sharp drop in depth to about 16,000 feet to the western edge of the Blake-Bahama Basin, at a downrange distance of about 220 nautical miles.

Water movements were studied recently in the missile range area by oceanographers of the Woods Hole Oceanographic Institute (WHOI) and the Chesapeake Bay Institute (CBI) of

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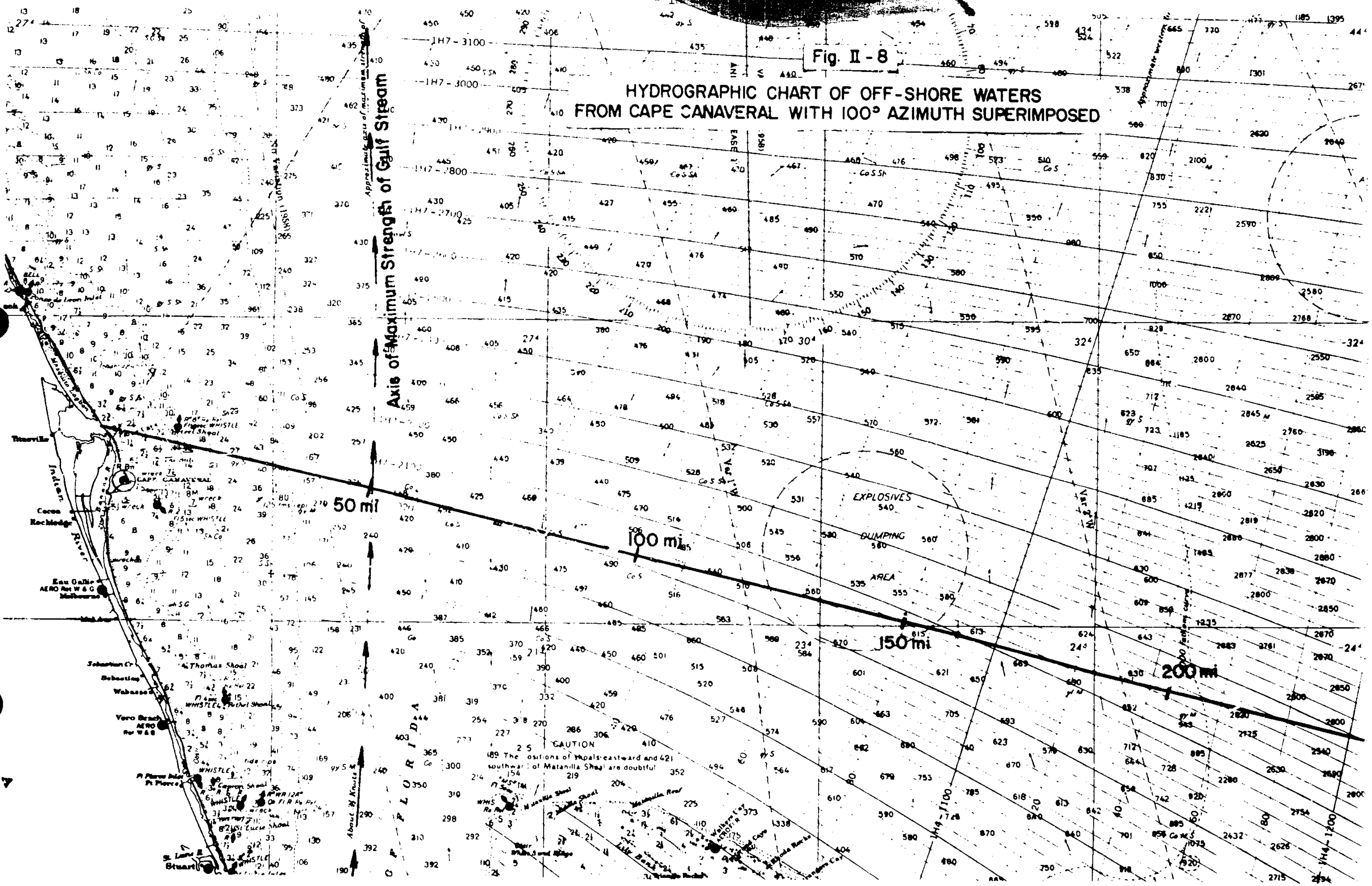

Fig. II - 8

HYDROGRAPHIC CHART OF OFF-SHORE WATERS FROM CAPE CANAVERAL WITH 100° AZIMUTH SUPERIMPOSED

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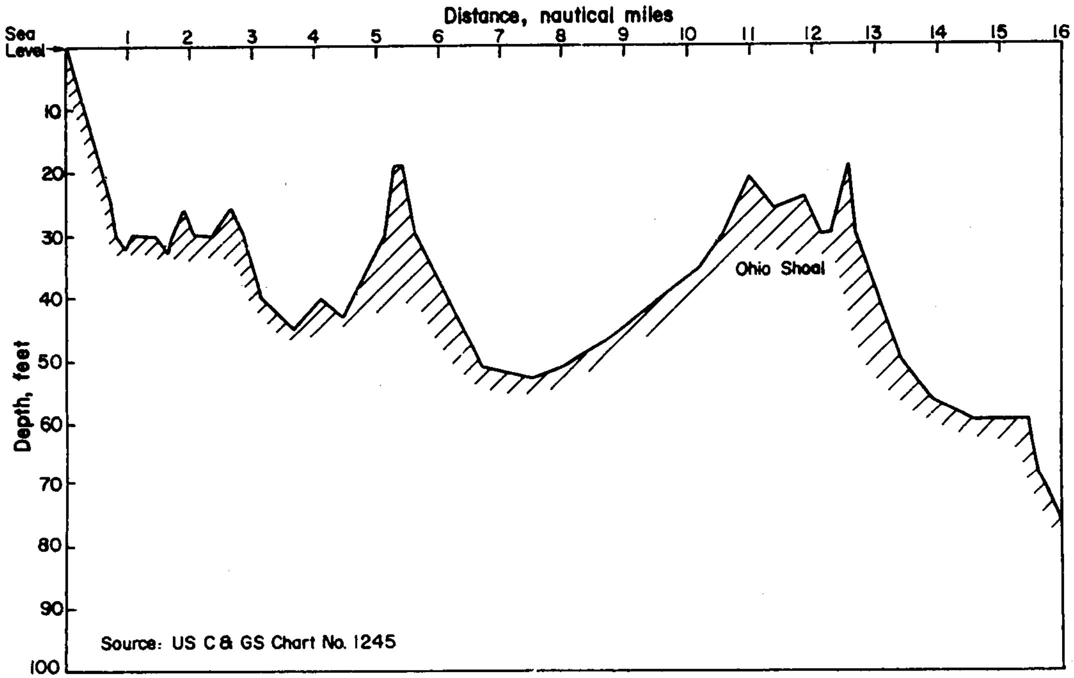


Figure II-9
Ocean Bottom Profile Along 100° Azimuth From Pad A, Cape Canaveral, To 16 Miles

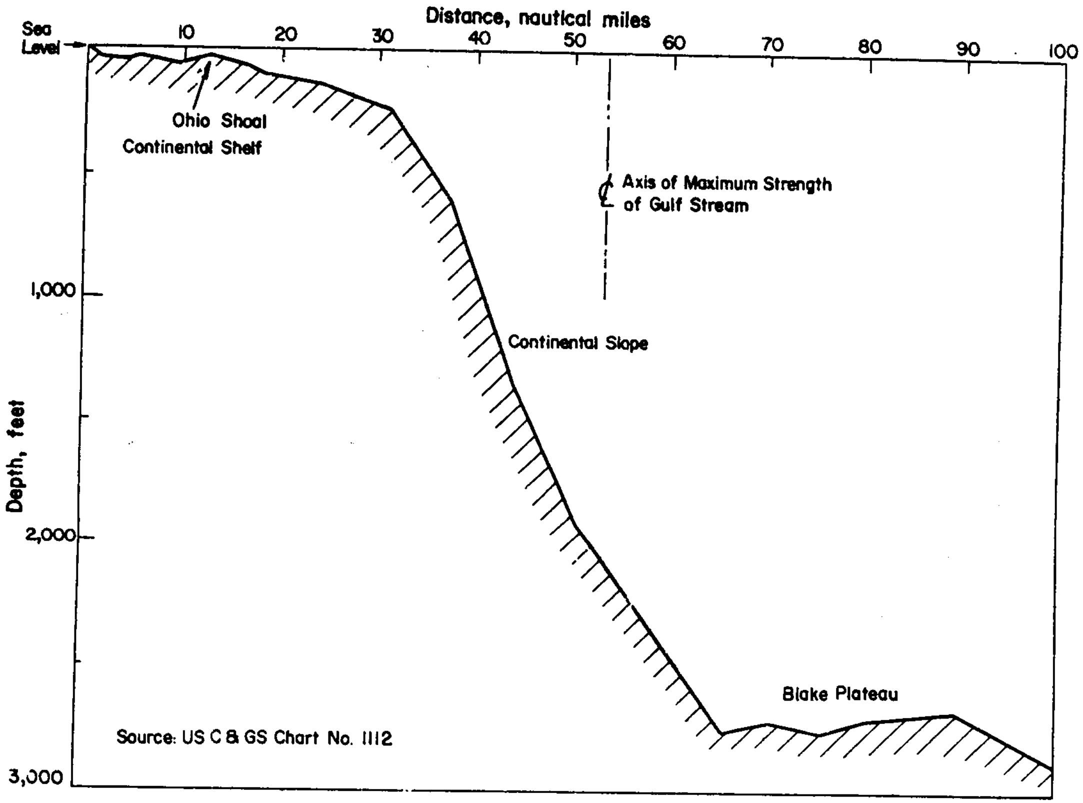


Figure II-10
Ocean Bottom Profile Along 100° Azimuth From Cape Canaveral Out To 100 Miles

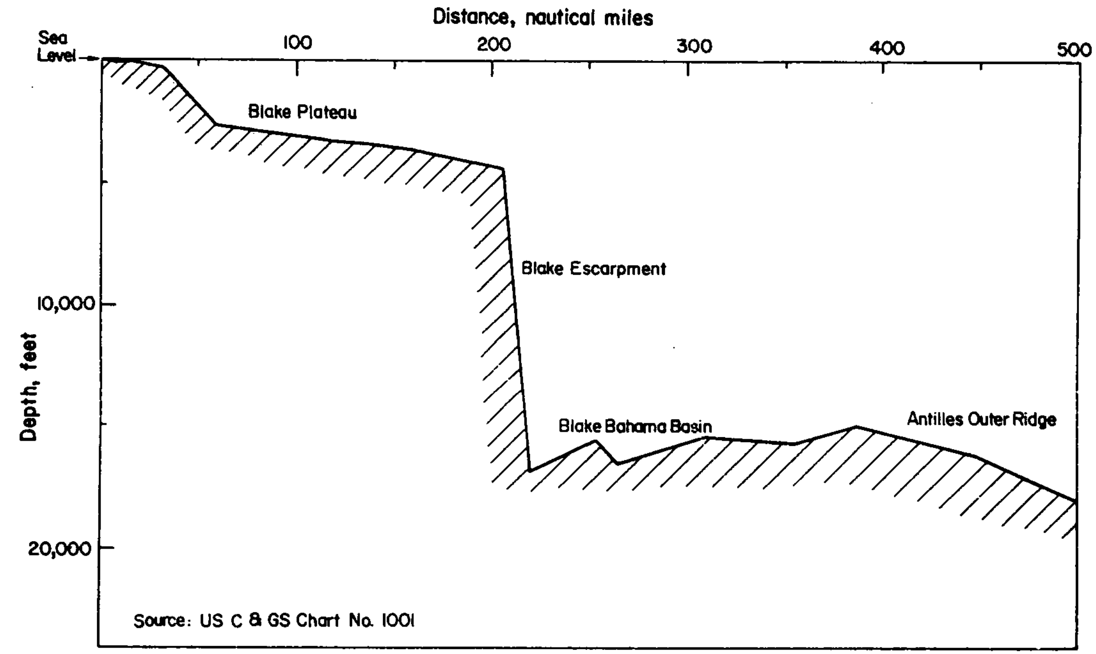


Figure II-11
Ocean Bottom Profile Along 100° Azimuth From Cape Canaveral Out To 500 Miles

the Johns Hopkins University. During March and April, 1962, non-tidal currents were examined by means of temperature, salinity, density, drift bottles, sea bed drifters, drogued telemetering buoys, moored current meters and fluorescent dye studies. WHOI results[3] indicate a shoreward direction of the current for the entire depth, surface to the bottom, in the region out to depths of 60 feet (16 nautical miles) at speeds of several miles per day. Wind-driven currents generally determine the current flow at the surface. In the region out to the sloping bank, the flow is slightly to the north with an easy reversal when the winds blow to the south. Water over the Blake Plateau flows to the north most of the time and is known as the Florida Current of the Gulf Stream with its axis over the western edge of the Blake Plateau. This section of the Gulf Stream begins at the Straits of Florida and runs northward to Cape Hatteras at a mean speed of 3.5 knots, transporting about 38 x 10^6 m^3/sec on the average.[4]

CBI reported[5] on the results of three injections of rhodamine B (a fluorescent dye) in the waters off Cape Canaveral which confirmed the WHOI drift bottle data. Strong winds from the north (25-30 knots) were necessary to reverse the general flow to the north over the shoal areas. The maximum concentration of the tracer dye in the diffusing patch dropped off approximately inversely proportional to the third power of time.

Further studies were carried out in the same off-shore region during August, 1962. WHOI[6] reported considerable differences in the nature of the coastal water from the winter-spring period. Pronounced statification existed with a strong density gradient at mid-depth separating the mixed layers above and below the gradient, in contrast to the nearly mixed water column observed in March and April. CBI[7] reported on three tracer experiments in August during which time no dye penetrated the sharp thermocline at 25 feet to the lower mixed layer which, in the March experiments, extended to the bottom (60-90 feet). Aerial photography with special optical filters facilitated the visual monitoring of the dye movements. Due to slower wind speeds in August than in March, less pronounced effects were noted due to wind-driven currents. Analytical results for the rate of

reduction of peak dye concentration were within the range of calculations performed following the spring runs.

5. Climatology and Meteorology

The meteorology of the Cape Canaveral area has been studied fairly extensively over the last several years in connection with the operations of both Patrick Air Force Base and the Cape Canaveral Missile Test Annex. Most of the information collected has been analyzed with the aim of establishing design and operational requirements for the vehicles to be launched at the site. Relatively little is presently available that has been directed at diffusion in the atmosphere although a recent study[8] has been conducted to develop estimates of diffusion parameters and an automated prediction system for toxic fuel dispersion. The WIND[9] system for collection of local meteorological data bearing on short-range atmospheric diffusion at Cape Canaveral was started in July, 1962. This system should provide an extremely useful basis for extending the network to the degree needed to properly evaluate the potentially larger range of hazard from nuclear operations.

The climatological and meteorological information used in this report was obtained from Patrick AFB, and from the Aeroballistics Division, George C. Marshall Space Flight Center.

a. General Climatology[10]

"The State of Florida is included in the source region of maritime tropical (mT) air. Therefore, it is primarily under the influence of this mT airmass. However, at times (usually winter) airmass changes do occur. For this reason, the local weather has been categorized into two general regimes: the frontal regime, from mid-September to mid-May; and the airmass regime, from June to September. In addition, the period June 15 through November 15 is referred to as the hurricane season. This overlaps into both regimes but is not a regime in itself. A summary of climatological means of several parameters is shown in Table II-1."

b. Atmospheric Stability

The stability of the atmosphere, relating the ease of vertical displacement of air volumes to the vertical temperature gradient,

TABLE II-1

CLIMATOLOGICAL DATA OF PATRICK AFB, FLORIDA

Parameter	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Temperature												
Maximum	85	87	91	95	95	99	97	97	95	91	89	85
Mean Maximum	70.1	70.4	74.5	78.4	82.8	85.6	86.6	87.8	85.9	80.9	75.1	70.9
Mean	63.2	63.8	67.9	72.5	77.1	80.3	81.1	82.2	81.3	76.4	69.3	64.3
Mean Minimum	56.2	57.0	61.0	66.4	71.3	74.5	75.5	76.5	76.4	71.6	63.3	57.4
Minimum	32	32	38	48	60	66	66	68	66	50	34	28
Mean Monthly Precipitation in inches	2.05	2.71	3.40	2.63	3.08	5.47	3.45	4.19	7.79	7.91	2.62	1.58
Mass Number of hours per Month with thunderstorms	0.7	1.3	4.5	5.0	12.6	14.4	21.6	23.3	13.0	4.5	2.2	0.8
Percent Frequency of ceilings less than 1500 feet and/or visibility less than 3 miles	7.4	5.8	4.6	2.5	1.6	2.3	1.2	1.4	2.9	0.9	3.2	5.9

is one of the major parameters affecting the dispersion of airborne contaminants. This factor is determined by comparing the measured temperature gradient to the adiabatic lapse rate (-1°C/100 meters). The latter is a "neutral" stability condition, i.e., one in which the vertical displacement of air can occur without transfer of heat into or out of the displaced air volume being required to adjust its density to that of its new environment. A lapse rate less than the adiabatic rate will impede vertical displacement and hence represents a "stable" atmosphere; one greater than the adiabatic will enhance vertical displacement, hence an "unstable" atmosphere.

Vertical temperature measurements have been made at Patrick Air Force Base by wiresonde, radiosonde, and tower measurements. Marshall Space Flight Center (MSFC) has analyzed temperature data from Patrick AFB and Cape Canaveral to develop design and operating criteria for rocket vehicles. Useful data on temperature stability patterns are available for both near-surface and upper atmosphere. However, for this preliminary hazard analysis, stability patterns were obtained from Patrick AFB in summary form,(10) which is reproduced in Table II-2.

TABLE II-2

FREQUENCY OF STABILITY CLASSES

(July 1958 - October 1961)*

	Frequency, %				
Local Time	Very Stable**	Mod. Stable**	Mod. Unstable**	Very** Unstable	No. of Cases
0000-9000	28	63	9	< 0.5	268
0900-1800	0	3	64	33	264
1800-0000	12	71	17	0	258

* Data show very little seasonal variation.

** Stability Class	VS	MS	MU	VU
ΔT (54'-6'), °F	≥ +3	0< <+3	-3< <0	≥ -3

From this summary, it is apparent that the occurrence of stable conditions is sufficiently high to warrant consideration of the inversion as the controlling regime for accident analysis. In this regard, additional semi-quantitative data from the Patrick AFB[10] meteorology group indicate:

"Low-level inversions greater than 1,000 feet deep are virtually nonexistent at Cape Canaveral except in the winter months, and then their duration is only a few hours. They occur after a cold frontal passage and a night of radiation cooling. The intensity of the inversions depend on how cold the airmass is initially, its position with reference to local area, cloudiness and time of day.

A relatively intense inversion may occur when a continental polar airmass covers Florida during early morning hours and is positioned such that the local area is under the influence of a land wind (northwest to west). If the night has been without clouds, an inversion of 5°C to 6°C can occur. Rarely, one greater than 10°C will occur if the continental polar air is unusually cold. Usually the inversion is from 1°C to 3°C. If the wind is from the water, surface inversions are extremely rare, although they may occur at about 2,000 to 3,000 feet; these usually do not exceed 2°C. The depth of inversions depends on the depth of the cold air. Therefore, a large continental polar, or sometimes Maritime polar, airmass will produce a deeper inversion than a shallow airmass. A strictly nocturnal inversion rarely extends higher than 1,000 feet, but one produced by a strong continental polar airmass may reach 5,000 to 6,000 feet."

Based on standard weather observations taken at the AMR, the Weather Bureau[11] has obtained estimates of the diffusion regimes at that site as a function of time of day and season. These regimes follow the classification of Pasquill[12] and range from class A - a strong lapse - to class F - a moderately stable atmosphere. To these, a seventh class F + (or G) has been added, which represents the extremely stable, light wind condition. The results of the Weather Bureau analysis are indicated graphically in Figures II-12, II-13, II-14, and II-15 by season.

CONFIDENTIAL

DIFFUSION INDEX FOR CAPE CANAVERAL [11]
SPRING (MAR. APR. MAY 1959)

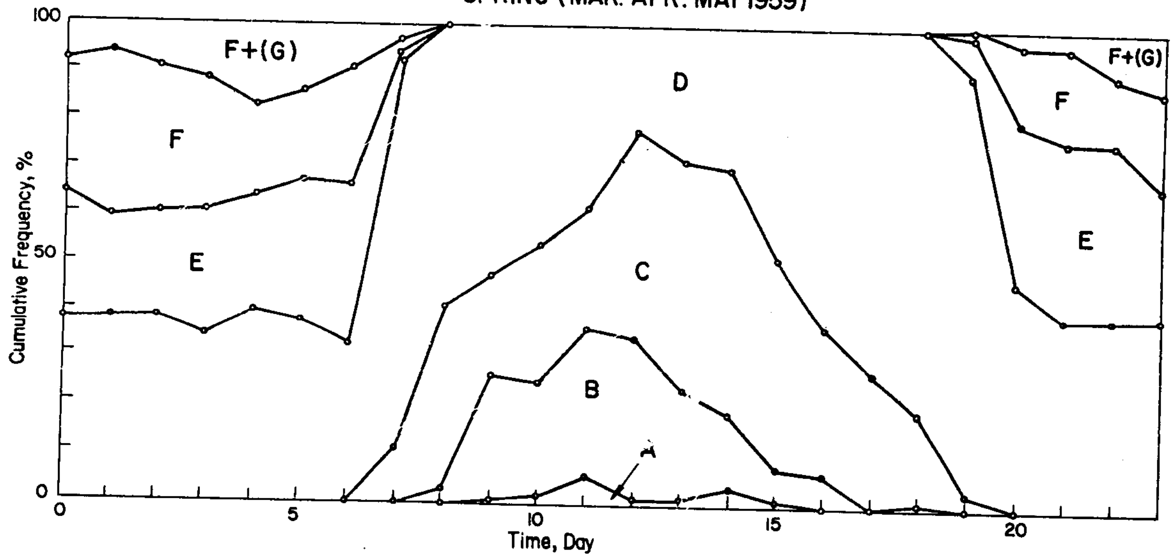


Figure II-12

CONFIDENTIAL

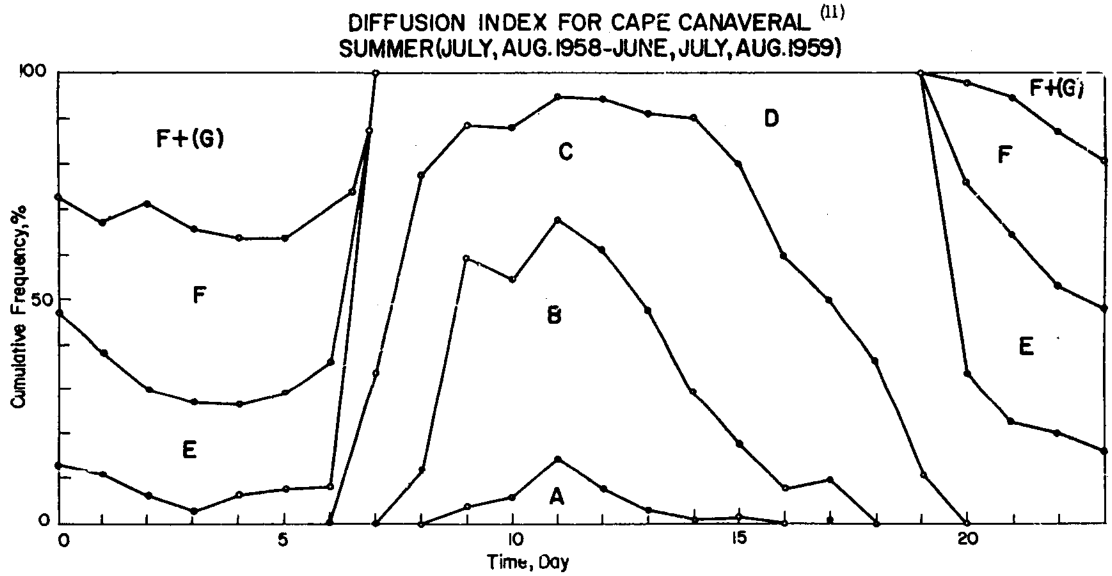

DIFFUSION INDEX FOR CAPE CANAVERAL (11)
SUMMER (JULY, AUG. 1958-JUNE, JULY, AUG. 1959)
100
50
0
Cumulative Frequency, %
0
5
10
15
20
Time, Day
F+(G)
F
E
C
D
B
A
F+(G)
F
E

Figure II-13

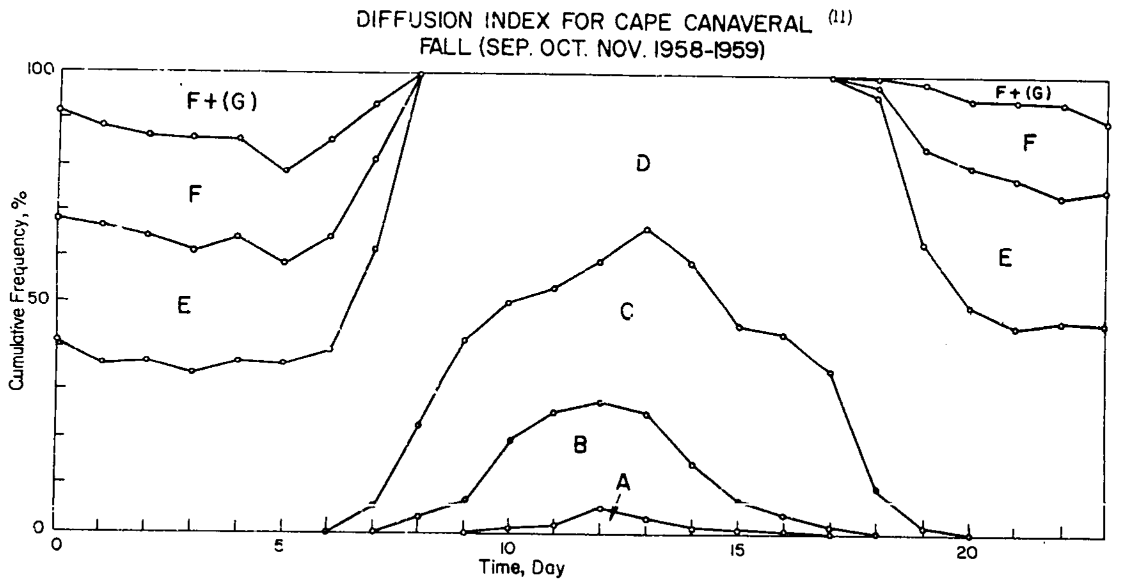
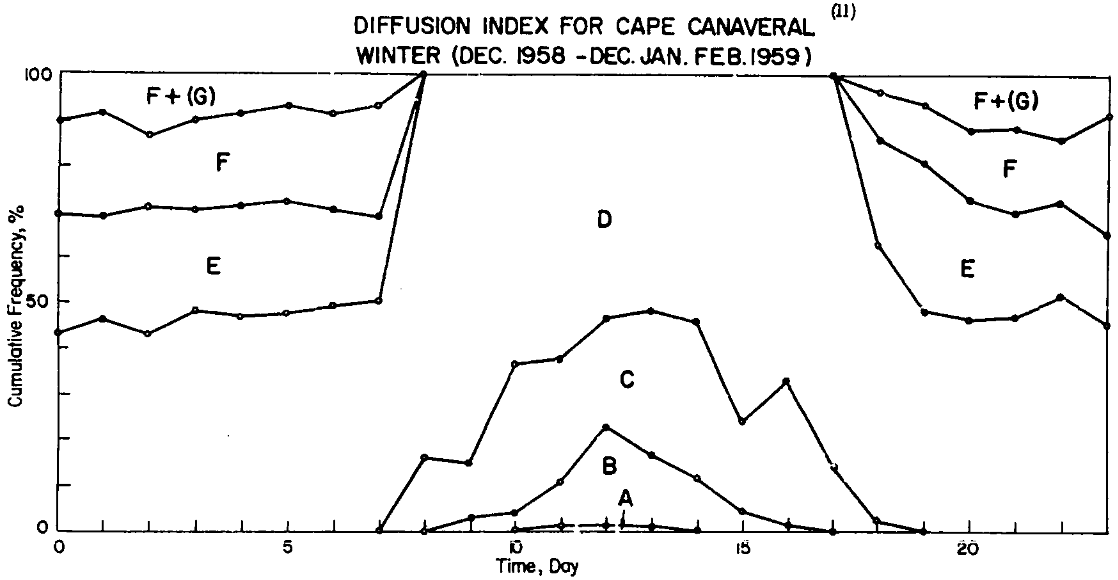


Figure II-14

CONFIDENTIAL



DIFFUSION INDEX FOR CAPE CANAVERAL (11)
WINTER (DEC. 1958 -DEC. JAN. FEB. 1959)
Cumulative Frequency, %
Time, Day
F + (G)
F
E
D
C
B
A
F+(G)
F
E
100
50
0
0
5
10
15
20

Figure II-15

Although the data in Table II-2 and in Figures II-12 through II-15 are not directly comparable, the general impression is substantially the same; stable conditions predominate at night, and neutral to unstable conditions prevail during the daytime.

c. Wind Structure

As mentioned above, surface and upper air winds have been collected at Patrick AFB and at Cape Canaveral. The major analyses of wind structure have been performed by the MSFC to determine design requirements for vehicles, and have not been specifically directed at problems of diffusion meteorology. The WIND system, previously mentioned, will provide a record of pertinent data collected at Cape Canaveral specifically for this purpose but covering a relatively small area. Additional sampling points will be required to determine the inland extent of the sea breeze, as well as the effects of land-water interfaces on cloud dispersion.

The most comprehensive summary of surface wind data available at present is that contained in a report from the MSFC,[13] which presents hourly and monthly wind roses, as well as time cross sections of the hourly and monthly scalar wind distributions, for selected frequencies of occurrence, based on data collected at 23.5-meter elevation at Patrick AFB from 1950 to 1959. This information has been reviewed to develop characteristics of significance in this hazard analysis. Since the frequency distribution of stability classes is presented by time of day (Table II-2), the data were computed to provide seasonal wind roses for the same three-diurnal periods - midnight to 9 a.m.; 9 a.m. to 6 p.m.; and 6 p.m. to midnight. These wind roses, presenting average wind velocity distributions for the winter (December to February), spring (March to May), summer (June to August) and fall (September to November) are shown in Figures II-16 through II-18 to indicate seasonal and diurnal patterns. For more detail, the original reference should be consulted.

Examination of these figures indicate that on-shore winds are not uncommon in any season during the periods when inversions

Figure II-16

AVERAGE QUARTERLY SURFACE WINDS FOR THE TIME PERIOD 0000-0900

(ELEV.=23.5 m, CALM<0.5 m/s)

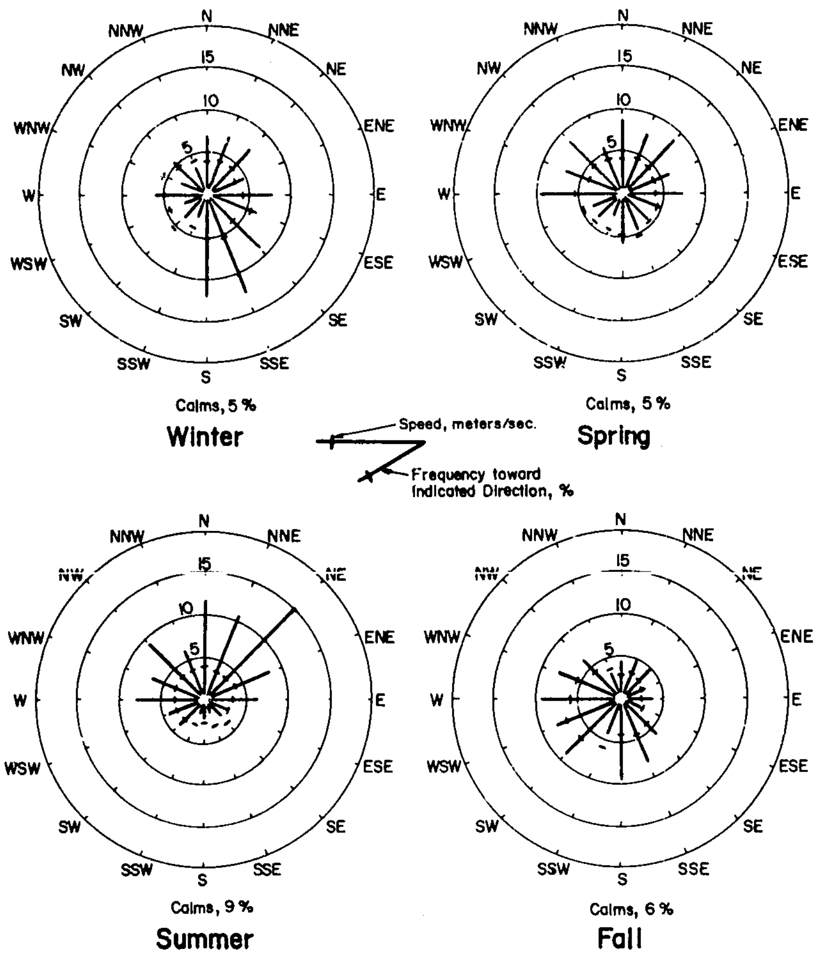


Figure II-17

AVERAGE QUARTERLY SURFACE WINDS FOR THE TIME PERIOD 0900-1800

(ELEV.=23.5 m, CALM<0.5 m/s)

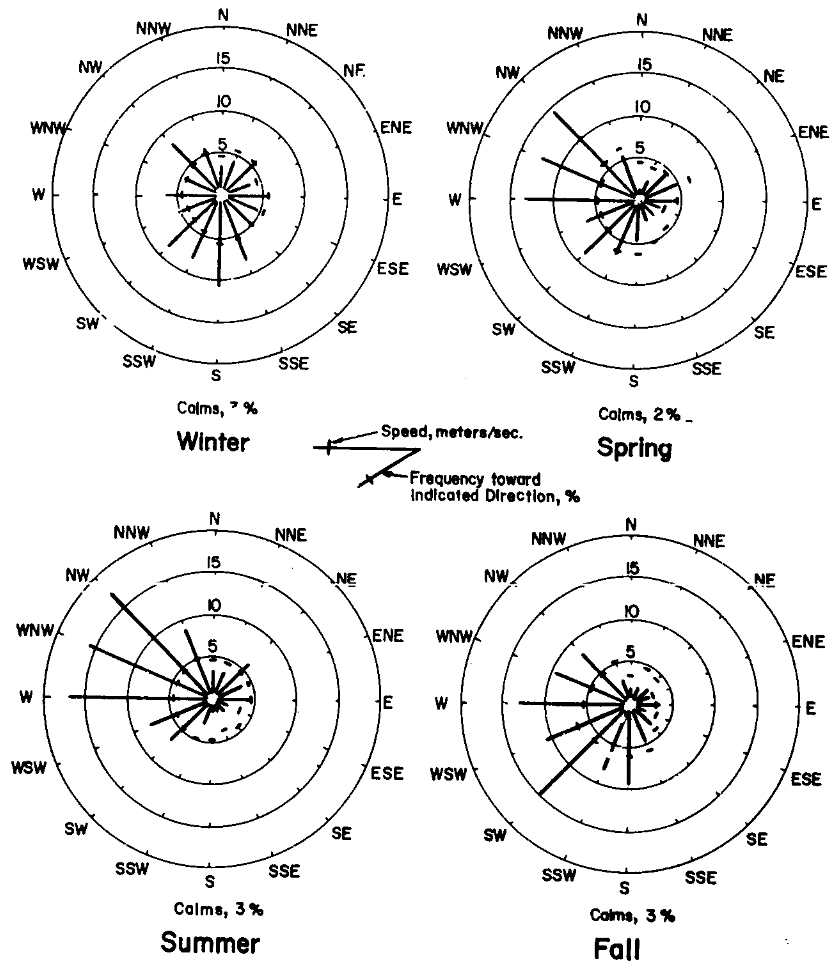
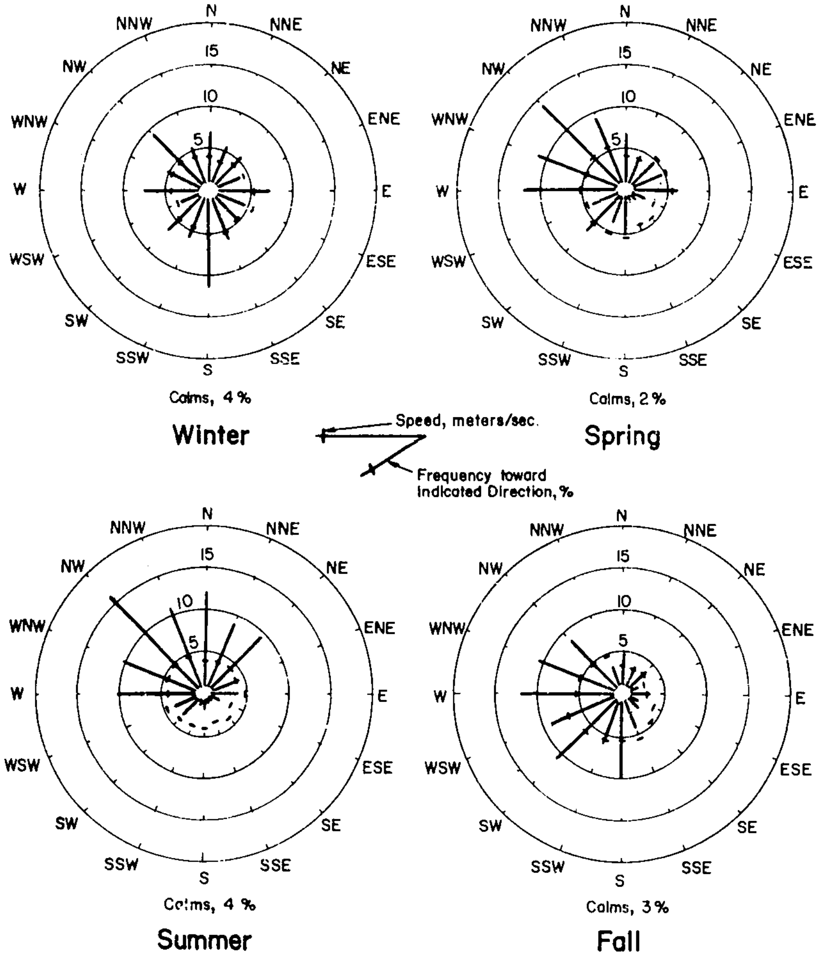


Figure II-18

AVERAGE QUARTERLY SURFACE WINDS
FOR THE TIME PERIOD 1800-2400
(ELEV.=23.5 m, CALM<0.5 m/s)



of some degree occur quite frequently from 1800 to 0900 hours. In the spring and summer, these winds are predominantly toward the west to north-northwest; in the winter, southward flow is enhanced; and in the fall, no directional preference is apparent. During the daytime period when unstable conditions prevail, on-shore wind tendencies are more pronounced, with somewhat higher wind speeds in evidence.

Another factor which is of importance in hazard analysis is the wind speed, since this determines the duration of exposure at a point downwind, as well as the delay time between the source and receptor. In most of the diffusion relationships, concentration is also indicated as being inversely proportional to wind speed. The median annual surface (23.5 m. altitude) wind speed is 5.0 m/sec. The highest wind speeds occur in the afternoon in all seasons; the lowest at night with a lull occurring between 0400 and 0800.

The median wind speeds also vary with direction and time of year: Table II-3 indicates the lowest monthly median speed occurring in each on-shore direction for the three diurnal periods treated. These are seen to be much lower than the annual median speed, as expected, and also to exhibit a difference factor of about 2.5 in minimum speed for different directions (i.e., NW vs SE) for the same diurnal period.

In the treatment of cloud dispersion, the wind profiles in the first few thousand feet of altitude play the most important role in those cases where a cloud rise is engendered by heat. These data are obtained with difficulty by using expendable tracking devices at relatively widely spaced intervals throughout the day. A treatment of this type of data[14] has produced a power law equation for computation of steady state wind distribution with height:

$$V = V_1 \left[\frac{z}{z_1}\right]^p \qquad \text{(II-1)}$$

where: V_1 is the wind speed at referenced height z_1,
V is the wind speed at height z, and
p is a non-dimensional empirical constant, with a value of 0.20 when the three-meter steady state wind is less than 15 m/sec.

TABLE II-3

MINIMUM MONTHLY MEDIAN ON-SHORE SURFACE WIND SPEEDS [13]

Direction Toward	Minimum Median Wind Speed, meters/sec., (month in which minimum occurred)		
	0000-0900 hrs.	0900-1800 hrs.	1800-2400 hrs.
SE	2.1 (7, 9)	2.1 (9)	1.3 (5)
SSE	1.5 (7)	2.8 (6)	1.3 (5)
S	1.3 (6)	2.8 (6)	1.3 (6)
SSW	1.8 (7,8)	2.6 (7)	1.8 (8)
SW	2.1 (7)	2.6 (4)	2.1 (7)
WSW	2.1 (7)	2.8 (1)	2.6 (7)
W	2.8 (6,7)	2.8 (1)	3.1 (7)
WNW	2.1 (3)	2.8 (8,12)	2.8 (7)
NW	2.1 (8)	2.6 (11)	3.3 (1,8)
NNW	2.1 (10)	3.3 (6)	2.8 (1)

Equation II-1 will be used in this report to relate wind speeds at altitudes up to 10 km to measured surface wind speeds, although due to the strong dependence of p on stability at low altitudes, this equation probably does not apply below about 1,000 feet.

d. Summary

The meteorology of the Cape Canaveral area has been defined reasonably well by the measurements made in the course of operation of Patrick AFB and the Cape Canaveral Missile Test Annex. More detailed analysis of vertical temperature profiles and wind speeds at various elevations could be made if time were available. For this preliminary evaluation, and consistent with the imprecision of other estimates made in the analysis, it is felt that a more detailed evaluation of these data is not warranted.

Stable atmospheric conditions are common during nighttime, and unstable conditions predominate during the day. Since by definition an accident may occur at any time, the analysis must examine the hazard occurring under both of these conditions with appropriate values for wind speed, etc. These estimates, as described below in Section III-A, must assume values for diffusion parameters and extent of transport which do not recognize the physical realities at the site. Data are needed on the inland extent of the sea breezes, and on the effect of land-water interfaces at the Cape on the dispersion of clouds. For a preliminary evaluation, however, the available data provide a satisfactory basis for an estimate of airborne transport.

6. Demography

a. Population Distribution

(1) On-Site

Only rough approximations of future population figures are available for the Cape Canaveral Complex. The present Cape Canaveral area has about 10,000 employees. It is estimated[15] that the Merritt Island Industrial Area will employ 2,500, including 1,500 construction workers; and the Complex 39 assembly and launch area, some 6,700, including 5,000 construction workers.

(2) Off-Site

Brevard is the fastest growing county in Florida, which was the fastest growing state in the country at the 1960 Census.[16] From 1950 to 1960, the population of Florida increased by 78.7 per cent and that of Brevard County by 371 percent.

According to the 1960 Census, the number of inhabitants in Brevard County was 111,435: 60,279 urban and 51,156 rural. Local groups estimate that the population of the county will increase by 88 percent (to a total of approximately 210,000) by 1970.

The main centers of population in the county are on the Atlantic Coastal Ridge along the Indian River. The barrier island strip on which Patrick Air Force Base is located is being rapidly developed for residential purposes. On Merritt Island, the area between Merritt Island City and the Cape Canaveral Missile Test Annex is steadily being converted into residential real estate.

The major population centers in the state of Florida are indicated in Figure II-1. The geographical population distribution based on the 1960 Census data in the off-site areas of Brevard County and in portions of counties adjoining it is shown in Figure II-19. A directional population distribution chart, Figure II-20, graphically showing the population of the off-site areas as a function of distance and direction from the assumed launching site, was prepared from the same data.

b. Land Usage

Approximately 40 percent of the total land area (660,480 acres) in Brevard County was in farms during the 1959 Census of Agriculture.[17] Between 1954 and 1959, the number of farms

Figure II-19

OFF-SITE POPULATION DISTRIBUTION (1960 CENSUS)

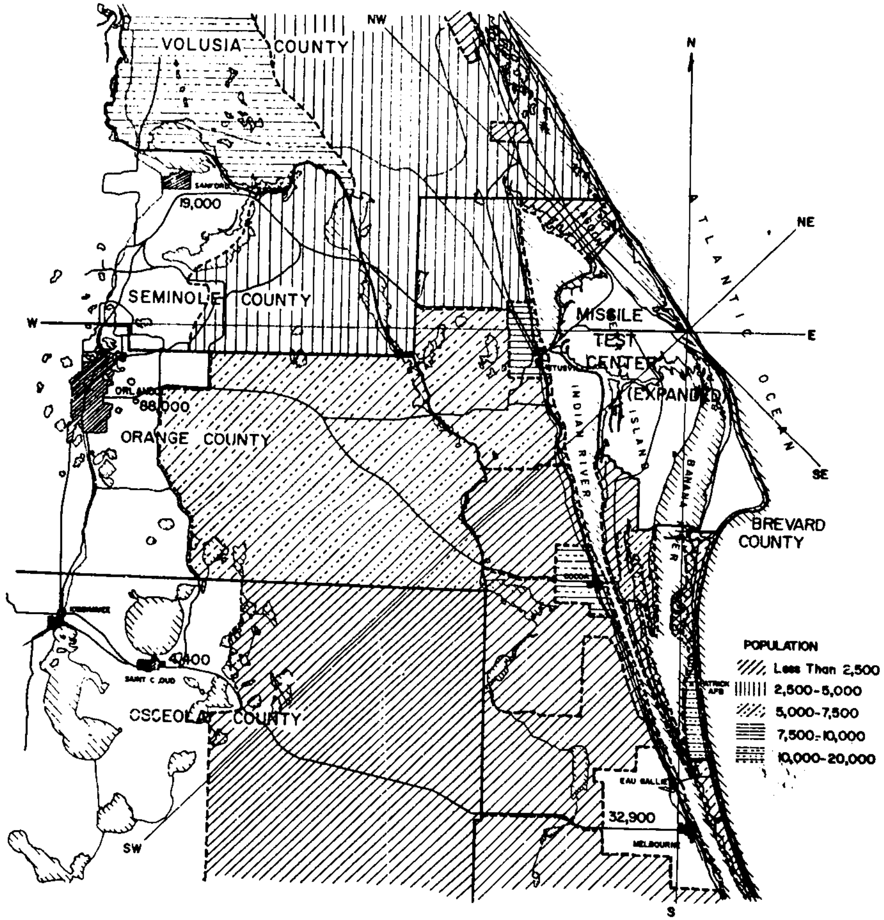
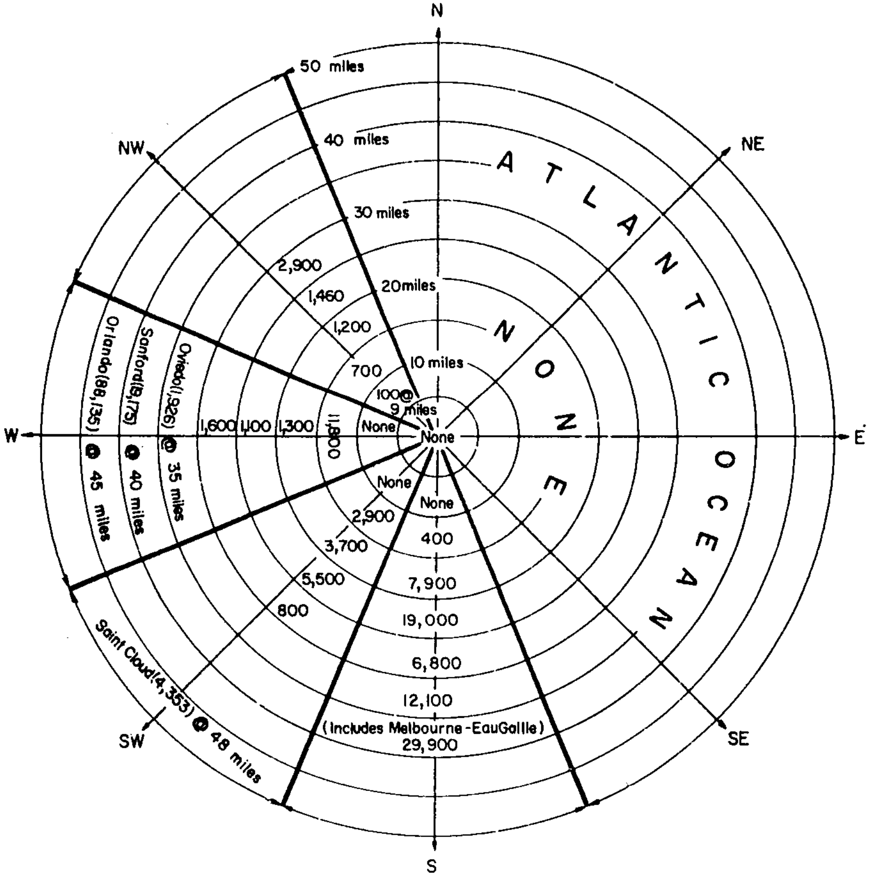


Figure II-20

OFF-SITE POPULATION DISTRIBUTION
AS A FUNCTION OF DISTANCE & DIRECTION
FROM COMPLEX 39, PAD A
(1960 CENSUS)



had decreased from 1,017 to 772 and the farm acreage from about 427,000 to 261,000. During this same period, however, the average value of the land and buildings per farm acre increased from $105 to $420.(17) Crops produced on farms in Brevard County are described in the following sections.

(1) Milk Cows

Twenty farms in Brevard County reported a total of 308 milk cows during the 1959 Census of Agriculture: 7 farms with 1 cow, 10 with 2 to 9 cows, and 3 with 50 or more cows. The total sales of milk and cream reported by 5 farms for 1959 was $135,000. The location and size of the herd of the three principal dairies in Brevard County are: (1) Titusville, 60 cows; (2) Eau Gallie, 50 cows; and (3) Malabar, 80 cows. These dairies pasture-feed their cows. All milk sold is shipped to Daytona Beach, where it is processed for sale to the consumer. During processing, the Brevard County milk is probably mixed with milk received from other areas. In Bithlo, Orange County, there are three dairies which have a total of 610 cows. The Orange County cows are fed with celery stripping and citrus pulp, and they are also pastured.(18)

(2) Eggs and Poultry Meat

The amount of egg production in Brevard County is considered to be relatively small. Poultry farming in the county is principally in the northern part, where there are approximately 10,000 chickens. These birds are kept in cages and feed is brought to them. The sale of poultry meat in the county is considered minimal.(18)

(3) Vegetables

Vegetable farming is carried out chiefly to the south of Cape Canaveral in the Melbourne area, during the spring and fall. In Melbourne there is a tomato canning plant. Some farmers take fresh produce to Orlando, where they sell it directly to consumers.(18)

(4) Beef Meats

There are approximately 50,000 head of beef cattle in the St. Johns River Valley, where most of the grazing is carried out in the county. These cattle are also given hay and hay silage. There are no meat packing plants in Brevard County.[18]

(5) Citrus Products

There are extensive citrus groves (approximately 10,000 acres) along the U. S. 1 Highway north of Titusville. Along the Indian River from Titusville to Cocoa, there are also citrus orchards. South of Cocoa, there are scattered citrus groves as far as Eau Gallie. On Merritt Island, between Merritt Island City and the Proposed new boundary of the Cape Canaveral Missile Test Center, there are also several thousand acres of citrus trees. Citrus fruit from the county is sold principally as fresh fruit. Six commercial packing houses in Cocoa ship carloads of fruit daily during the fruit season; and in the county there are numerous shippers of fresh citrus gift packages. Approximately one million boxes of citrus fruit are shipped every year. At Port Canaveral there is a frozen citrus juice plant which processes the juice in bulk quantities only; it does not can it in small containers for sale directly to the consumers. Citrus fruit from all over the state, not just from Brevard County, is processed in this plant.[18,19]

c. Water Usage

(1) Drinking and Domestic

(a) Surface Water

Large quantities of surface water are available at many places in Brevard County. The St. Johns River, throughout its length in the county, constitutes a potential source of water for municipal, industrial, and agricultrual supplies. The river flows through several large lakes which are natural reservoirs that have large storage capacities. The amounts of water

in storage in the lakes at their lowest stages during the period of record were as follows: Lake Helen Blazes, 650 million gallons; Sawgrass Lake, 650 million gallons; Lake Washington, 3,200 million gallons; Lake Winder, 1,080 million gallons; and Lake Poinsett, 1,660 million gallons. During 5 percent of the time of record, Lake Poinsett contained at least 9.5 billion gallons of water. The analyses of water from the St. Johns River show that the river is low in mineral content but rather high in color at the source area. The hardness, chloride content, and dissolved solids generally increase downstream from the source.

The streams that flow eastward out of the Atlantic Coastal Ridge to the Indian River continue to flow even during periods of low rainfall. The analyses of water from these streams indicate that several offer promise for water-supply development.[2]

(b) Ground Water[2]

The source of the largest supplies of ground water in Brevard County is the Floridan aquifer. The chloride content of these waters ranges from 32 to 14,500 ppm, the pH from 7.3 to 8.1. Generally, the quality of the artesian water is unsuitable for public drinking supplies, except in two small local areas of recharge near Titusville, and west of the St. Johns River. The Floridan aquifer is used principally as a source of water for agricultural purposes (irrigation) and stock watering; it is also utilized for domestic supplies in those areas of the county where the quality is not objectionable and where other suitable water is not available.

The quality of the nonartesian water is generally superior to that of the artesian water. The high chloride content and hardness of samples of nonartesian water are due, at least in part, to contamination by upward-flowing artesian water. The chemical composition of water from the nonartesian aquifer is such that the water after chlorination and treatment for iron, color, and hardness is suitable generally for all purposes. The nonartesian aquifer in the Atlantic Coastal Ridge is the source of supply for several munici-palities and hundreds of privately owned wells. Withdrawal of water from the nonartesian aquifer by wells for domestic and commercial purposes is extensive in areas not served by public water sys-tems. Most nonartesian wells are small 1 1/4-inch to 2-inch sand-point wells which produce less than 30 gallons per minute.

(c) Municipal Water Supplies[2]

Because of the rapid urbanization in this area, each of the four major cities in Brevard County has, during the past five years, either gone to new sources of water supply and improved its facilities or is in the process of doing so.

Six new nonartesian wells (24 inches in diameter and 110 feet deep) drilled in 1957 supply the present needs of Titusville and its surrounding area. The treatment plant has a rated capacity of 1 1/2 million gallons per day and a finished water storage of a half million gallons. Chlorination is the only treat-ment of the water prior to distribution. The Titusville water distribution rate, which was 300,000 gallons per day five years ago, averaged about one million gallons per day during 1957.

Prior to August, 1957, the city of Cocoa obtained its waters from Clear Lake and adjacent surface water supplies. Increased withdrawal from these sources caused an increased mineralization to the extent that, even after treatment, the delivered water often con-tained chloride and dissolved solids in excess of desirable concentrations. Clear Lake was unable to meet the increased demands of Cocoa and was dis-continued as a source of water supply in August, 1957, when a new well field which was developed about 18 miles west of Cocoa, in Orange County, began operation.

This well field also supplies Rockledge, Merritt Island, Cape Canaveral, Patrick Air Force Base and the barrier island beach area north of the Base.[18,19] Distribution of water for Cocoa increased from less than 1,000,000 gallons per day to approximately 6,000,000 gallons per day in 1958. Capacity of the treatment plant is 12,000,000 gallons per day with a storage capacity of 1,500,000 gallons of finished water. The treatment provided by the plant is chlorination, aeration, softening, and fluoridation. Clear Lake could still be used as a small water supply, as before, and could be expected to provide water of suitable quality during normal rainfall conditions. Cocoa is also considering the possibility of using Lake Poinsett as a source for its municipal water supply.[18]

The current supply at Eau Gallie is obtained from seven nonartesian wells that are 40 to 60 feet deep, and from one artesian well that provides approxi-mately 50 percent of the delivered water. Distribu-tion of treated water increased from 286,000 gallons per day in June, 1956, to 933,000 gallons per day in June, 1958. The rated capacity of the treatment plant is 400,000 gallons per day with a storage capacity of 450,000 gallons of finished water. Treat-ment of the water prior to distribution consists of chlorination and softening.

Melbourne is the only city in Brevard County which presently uses a lake for its municipal water supply. Water from Lake Washington is used to supply the city and also the barrier island strip from Patrick Air Force Base southward.[18] Until recently, Melbourne obtained its municipal water solely from shallow, nonartesian wells located west of the city in the coastal ridge. The current capacity of the treatment plant is approximately 1,000,000 gallons per day with a storage capacity for finished water of 750,000 gallons. Because of the tremendous increase in population, the capacity of the plant is being increased to 10,000,000 gallons per day. Current treatment is chlorination, aeration, and softening.

All of Orange County, including Orlando, obtains its municipal water from wells. Orlando considers its nearby lakes as a standby source.[18]

(2) Irrigation[2]

Large quantities of surface water are available at many places in Brevard County. The St. Johns River, with its many lakes, constitutes a potential source of water for municipal, industrial, and agricultural supplies. Several of the streams which flow eastward from the Atlantic Coastal Ridge to the Indian River offer promise for water-supply development.

At present, however, the Floridan aquifer is the principal source of water for agricultural purposes in Brevard County. Artesian water within the county generally has a concentration of mineral ions which exceeds the maxima recommended for domestic or industrial supply. The principal uses of these waters are for irrigation and stock watering. Although the mineral content of most of these waters seems excessive for irrigation purposes, citrus production appears good even when the water contains as much as 2,000 ppm of chloride. Frequent flushing of the soil by rain is perhaps the main reason that water of such high mineral content is tolerated by the crops without crop burning.

Subirrigation is used extensively in Brevard County by raising or lowering the water level in the ditches surrounding the irrigated field. The water table is maintained in dry seasons by flooding the ditches with water from artesian wells. Water is maintained in the field laterals until the water table rises to within 12 inches of the surface, then the wells are shut off and the water table is allowed to recede by plant transpiration, evaporation, and downward percolation to 24 inches below land surface. When the water table is at a depth of 24 inches, the wells are turned on again and the procedure is repeated. The minimum amount of water, in addition to precipitation, required for efficient operation of the system is about

7.5 gallons per minute, per acre irrigated, if the system is operated for 24 hours a day. One acre requires about 11,000 gallons per day for optimum grass growth.[2]

Large acres of pasture and grove lands are subirrigated with artesian water. Some of the water that is used for irrigation percolates downward and recharges the non-artesian aquifer. Subirrigation along the coastal ridge is difficult because it requires a large volume of water to bring the water table up near the root zone of the plants. Many residents in the county use water pumped from the nonartesian aquifer for lawn irrigation.

During the past few years, several thousand acres of the St. Johns River Valley between Lake Poinsett and the Indian River County line have been cleared and diked off for improved pasture. Artesian wells have been drilled in the area to irrigate the pastures during periods of low rainfall. The irrigation wells are usually located on the highest land to be irrigated and the water is distributed by gravity through the system of main ditches and field laterals.

The major citrus growing areas in Brevard County are along the Indian River, from the south edge of the city of Rockledge to the Volusia County line, and on Merritt Island. In these areas, artesian water with as much as 1,800 to 2,000 ppm of chloride is used for subirrigation. Some groves have been badly burned and in some cases killed by overirrigation with salty artesian water.

(3) Fishing

(a) Commercial Fisheries[20]

In 1960 the commercial fisheries landed in the four counties (Volusia, Brevard, Indian River, and St. Lucie) a total of 11,562,000 pounds of fishery products valued at $1,595,000 to the fisherman. Table II-4 shows the value and weight landed, by species. The four species (shrimp, spotted sea trout, blue crab,

TABLE II-4

FISHERIES OF THE CAPE CANAVERAL AREA
(VOLUSIA, BREVARD, INDIAN RIVER, AND ST. LUCIE COUNTIES)
SHOWING VALUE TO THE FISHERMAN AND POUNDS LANDED (20)
(1960)

Species	Dollar Value	Pounds
Group 1:		
Shrimp	691,000	2,054,000
Spotted Sea Trout	188,000	796,000
Blue Crab	172,000	3,423,000
Red Snapper	120,000	406,000
Sub-total -----------------	1,171,000 (~75% of total)	6,679,000 (~57% of total)
Group 2:		
Spot	72,000	788,000
Black Mullet	69,000	1,458,000
Bluefish	60,000	567,000
Pompano	58,000	87,000
Sub-total -----------------	259,000 (~16% of total)	2,900,000 (~25% of total)
Group 3:		
King Mackerel	27,000	216,000
King Whiting	24,000	275,000
Spanish Mackerel	19,000	194,000
Groupers	19,000	154,000
Red Drum	15,000	96,000
Menhaden	14,000	495,000
Sub-total -----------------	118,000	1,430,000
Total ------------------------	1,548,000	11,009,000
Misc. species	47,000	553,000
GRAND TOTAL -----------------	1,595,000	11,562,000

and red snapper) dominate the fishery with nearly 75 percent of the value and about 57 percent of the weight. The eight species in groups 1 and 2 represent 91 percent of the value and 82 percent of the weight of fishery products landed in the area.

The commercial catch, by county, is shown in Table II-5. Brevard County leads the other three counties, with shrimp contributing nearly two-thirds of the value.

Most of the commercial fishery products are obtained from a relatively narrow band of water adjacent to the coast and from the estuarine waters. Red snapper and grouper, however, are taken offshore, on the reefs.

Shrimp is by far the most valuable fishery in the area, Brevard County having the most productive fishing grounds. Fishing is conducted in a narrow belt adjacent to the coast, and the best fishing occurs during late fall and winter. Principal specie taken is white shrimp, a migratory specie which moves into and out of the area, and which is taken by trawling. Exploratory fishing has indicated that there is a potentially valuable fishery for the royal red shrimp in waters from 150-250 fathoms, just offshore from the edge of the continental shelf and in the Gulf Stream.

The fishery for spotted sea trout is conducted principally in estuarine waters. Migrations of this species are not well known, but movements are probably limited. Blue crab fishing, a relatively new but increasingly important fishery, is largely in the estuaries by means of trotlines, crab pots, and also shrimp trawls. Red snapper occurs mainly on banks or reefs in offshore waters on the continental shelf and is fished largely by hand lines. Spot are found adjacent to the coast and in the estuaries; and black mullet is taken in abundance in the inshore waters. Bluefish, which is fished adjacent to the coast, appears to be migratory, moving northward

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TABLE II-5

FISHERIES OF THE CAPE CANAVERAL AREA BY COUNTIES SHOWING VALUE TO FISHERMAN AND POUNDS LANDED (20)
(1960)

	Volusia County		Brevard County		Indian River County		St. Lucie County	
Species	Dollar Value	Pounds	Dollar Value	Pounds	Dollar Value	Pounds	Dollar Value	Pounds
Shrimp	288,000	858,000	401,000	1,190,000	-	-	2,000	6,000
Spotted Sea Trout	53,000	225,000	62,000	262,000	28,000	119,000	45,000	190,000
Blue Carb	25,000	496,000	39,000	777,000	65,000	1,300,000	43,000	850,000
Ped Snapper	46,000	155,000	25,000	85,000	5,000	18,000	44,000	148,000
Subtotal --------	412,000	1,734,000	527,000	2,314,000	98,000	1,437,000	134,000	1,194,000
Spot	5,000	54,000	23,000	252,000	32,000	350,000	12,000	132,000
Black Mullet	24,000	506,000	28,000	595,000	12,000	251,000	5,000	106,000
Bluefish	100	900	600	6,000	8,000	75,000	51,000	485,000
Pompano	700	1,000	42,000	63,000	7,000	10,000	8,000	13,000
Subtotal --------	29,800	561,900	93,600	916,000	59,000	686,000	76,000	736,000
King Mackerel	1,000	8,000	5,000	42,000	100	1,000	21,000	165,000
King Whiting	4,000	44,000	18,000	203,000	-	200	2,000	28,000
Spanish Mackerel	-	200	1,000	12,000	200	2,000	18,000	180,000
Groupers	6,000	54,000	3,000	22,000	500	4,000	9,000	74,000
Red Drum	9,000	58,000	2,000	12,000	2,000	15,000	2,000	11,000
Menhaden	-	500	1,000	45,000	12,000	430,000	1,000	19,000
Subtotal --------	20,000	164,700	30,000	336,000	15,000	452,000	53,000	477,000
Total -----------	461,800	2,460,600	650,600	3,567,000	172,000	2,575,000	263,000	2,407,000
Misc. Species	14,000	179,000	10,400	90,000	3,000	57,000	20,000	227,000
GRAND TOTAL -----	475,800	2,639,600	661,000	3,657,000	175,000	2,632,000	283,000	2,634,000

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in the spring from its wintering grounds in Florida and southward again in the fall. Pompano is caught in the inshore waters, particularly the estuaries.

An immense scallop bed, extending from Daytona Beach to Ft. Pierce, at depths of from 10 to 30 fathoms and having commercial concentrations over a 1,200 square mile area, has recently been discovered. This resource appears to have the makings of a valuable new fishery.[20]

Oyster fishing is a seasonal operation which is carried out in the Sebastian Inlet area, on the Indian River.[18]

No data have been available on the intrastate and interstate shipment of fish caught in the four-county area; nor are any data yet available on commercial value of the scallop bed.

(b) Sport Fishing

Sport fishing in the area has great economic importance, and it supplies a large quantity of food to thousands of persons. The important species are those indicated in the discussion of commercial fisheries. In addition, there is also sport fishing for larger game fish such as sailfish, marlin, tuna, barracuda, and wahoo in the Gulf Stream. Sports fishermen also take quantities of small fish in the estuaries and other inshore waters, but many of these fish do not support a commercial fishery of importance.[20]

In the Banana and Indian Rivers, the best fishing is from the bridges or from the banks while wading along the edge of the water. The Cocoa causeway, running across both rivers, acts as a dam, forcing the fish to swim under the bridges. There is also surf fishing for such species as channel bass, blue fish, snook, flounder, sea trout, pompano, and drum. Out of Port Canaveral, some sportsmen troll from an outboard motor boat, or anchor over an offshore wreck lying just under the water and fish for such game fish as red snapper, amberjack, and grouper.[21]

According to a 1957 report[22] entitled, "Catches of Fish by Charter Boats from Florida's East Coast," dolphin was the most abundant species occurring in the catches, followed by kingfish, bonito and grouper. These species together accounted for about 68 percent of the total number of fish caught on the trips sampled. Amberjack was the greatest in terms of weight - the next three species, in order of weight caught, being dolphin, kingfish, and sailfish. These four species together accounted for 67 percent of the total weight of fish caught during the trips sampled.

A sample of Florida residents selected from street directories showed that about 65 percent of the households in Florida contained one or more anglers. From a telephone survey made during 1957-58, panel members were obtained who gave information concerning fishing activities. They submitted 759 forms which showed their catch and effort over a period of ten months. These forms contained information on about 1,000 trips with an average of over two anglers on each trip. Private boat angling accounted for 52 percent of the total trips. Bridge, pier and jetty fishing accounted for 34 percent and the remaining 16 percent utilized charter, rental and party boats. These anglers reported that on 178 of their trips no fish were caught. Those who caught fish reported 58 species of fish and 5 species of shellfish. The total number of fish caught was 17,000 with an approximate weight of 25,000 pounds. Anglers retained almost 65 percent of this catch. About 34 percent of the total catch consisted of spotted sea trout and about 9 percent was Spanish Mackerel.[23]

The St. Johns River provides a sport fishery of great value. Fifty-two species of fish have been found in these waters. Between June, 1955, and May, 1956, the U. S. Fish and Wildlife Service conducted an intensive study[24] on the economic aspect of the sport fishery in the St. Johns River and river lakes upstream from the Devil's Elbow near Palatka. Over

2,700 anglers were interviewed in order to obtain an estimate of average expenditures per trip by anglers in each of twelve areas under study. As shown in Table II-6, the economic value of the sport fishery in the Brevard County areas was well over half a million dollars annually. If the remaining area downstream to Palatka is included, the value was almost $3,000,000 annually. Because of the tremendous increase in population in the area, particularly Brevard County, since the dates of this study, the figures in Table II-6 are considered to be low estimates of the present fishery value.

(4) Recreation

In addition to the sport fishing discussed above, other water sports in the Greater Cocoa Chamber of Commerce, there are annually about 80,000 transient tourists and 7,500 resident tourists in the area.

(a) Indian River Basin

The Florida Game and Fresh Water Fish Commission[25] has been interested in the Indian River-Merritt Island-Banana River area for many years because of the great concentration of waterfowl found in that region. The Brevard County estuaries harbor the largest number of waterfowl of any specific region in the state. Approximately 11,000,000 of the 14,000,000 duck days recorded for five major areas in the state were noted in the Brevard estuaries. (Briefly, a duck day represents one duck on an area for one day. To compute duck days, the number of ducks seen on two successive flights is totaled and averaged, and the average is multiplied by the number of days occurring between the dates of the two inventories. The procedure is repeated with results of the next inventory, etc. Coot days are computed the same way, and the sum of duck days and coot days equals waterfowl days.) Waterfowl are highly migratory. In 1954, a banding program was instituted at Titusville. From

TABLE II-6

FISHERY VALUES - ST. JOHNS RIVER BASIN (1955-56)

GROUP	ANGLERS	TOTAL VALUE
Lake Wilmington	3,904	$ 47,121
Fellsmere Canals	8,621	40,863
Melbourne Area	14,934	131,568
Cocoa Area	27,970	169,218
Christmas Area	22,582	129,846
Lake Harvey Area	63,610	289,425
Lake Monroe	13,694	41,082
de Land Area	53,558	230,299
Lake Dexter Area	31,803	187,002
Astor Area	24,240	186,406
Welaka - Welaka Area	138,950	1,425,627
South Lake Area	6,684	21,857
Total for Basin	410,550	2,900,314

6,500 ducks banded, 114 were recovered: 39 from Florida and the remaining 75 from other states. Sixteen states, five Canadian Provinces and the Bahama Islands were found to harbor birds which spent the winter in Brevard County. Principal species of duck found during a 1955-56 inventory in the Merritt Island-Banana River area were pintail, baldpate, and scaup. There were also Canadian Geese and coot.

(b) St. Johns River Valley

The St. Johns River Valley has long been acclaimed as one of the best waterfowl areas in Florida. It is important not only for migratory waterfowl but for the native Florida ducks, as well.

Appreciable numbers of wintering waterfowl arrive in the valley about mid-November. A fairly constant population is maintained until mid-February, when a considerable portion of the pintails begin to leave central Florida. Average peak population is about 30,000; one-half of this number being coot. Among the more abundant species are ringneck, pintail, baldpate, blue-winged, and shoveller. Some coot remain in the valley during the summer, but normally few waterfowl remain after early April.

Duck days for the past ten years averaged 856,094 for the upper St. Johns River Valley. Coot days averaged 946,032 annually. In the fall of 1956, nearly 39,000 hunting stamps were sold. It is estimated(26) that about 4,000 to 5,000 mandays were spent in waterfowl hunting in this area and that the annual kill averaged between 10,000 and 12,000 birds. While the numbers and concentration of waterfowl in the St. Johns River Valley are much lower than the numbers of lesser scaup in the Indian River, their desirability is much greater.

Turkey and deer are hunted in the wooded areas adjacent to the Lake Washington marsh. Otter are trapped in moderate numbers by local residents.

There is a frogging industry of moderate proportions south of Lake Washington. Harvesting of alligators for hides, legal and otherwise, takes place in sections of the St. Johns River Valley.

B. DOWNRANGE ENVIRONMENT

A detailed specification of the downrange environment similar to that presented above for the launch site is not feasible, since the area of concern for RIFT covers tens of thousands of square miles; and for operational vehicles, about half the earth's surface is potentially affected. Obviously, a description can only be general and non-specific under these circumstances. For this reason, the following discussion will be general, and limited to a consideration of the area covered by the RIFT flight path and to a general indication of environmental factors of significance.

1. RIFT Trajectory

The reference trajectory assumed to permit delineation of affected areas was taken from a study by MSFC.[27] Figure II-21 indicates this flight path, with a launch azimuth of 100°, presently felt to offer the best compromise between ease of tracking and command communication, and safety of ground stations in the event of abort. A single SN operating period trajectory was selected as the one providing an impact point farthest downrange.

A deviation in azimuth of $\pm 5^{\circ}$ is also indicated in this figure to indicate the general range of areas that may be covered by the RIFT flights.

2. Oceanography

A considerable body of literature is available which describes the general characteristics of the oceans of the world. Perhaps one of the best known in "The Oceans" by Sverdrup, et al.[4] A literature survey of the downrange AMR area has been prepared by the Woods Hole Oceanographic Institute[28] for the Atomic Energy Commission covering the fields of hydrography, bathymetry and the fisheries of this area. Although specific studies of selected RIFT impact areas may be warranted, some general observations may be drawn from information presently available.

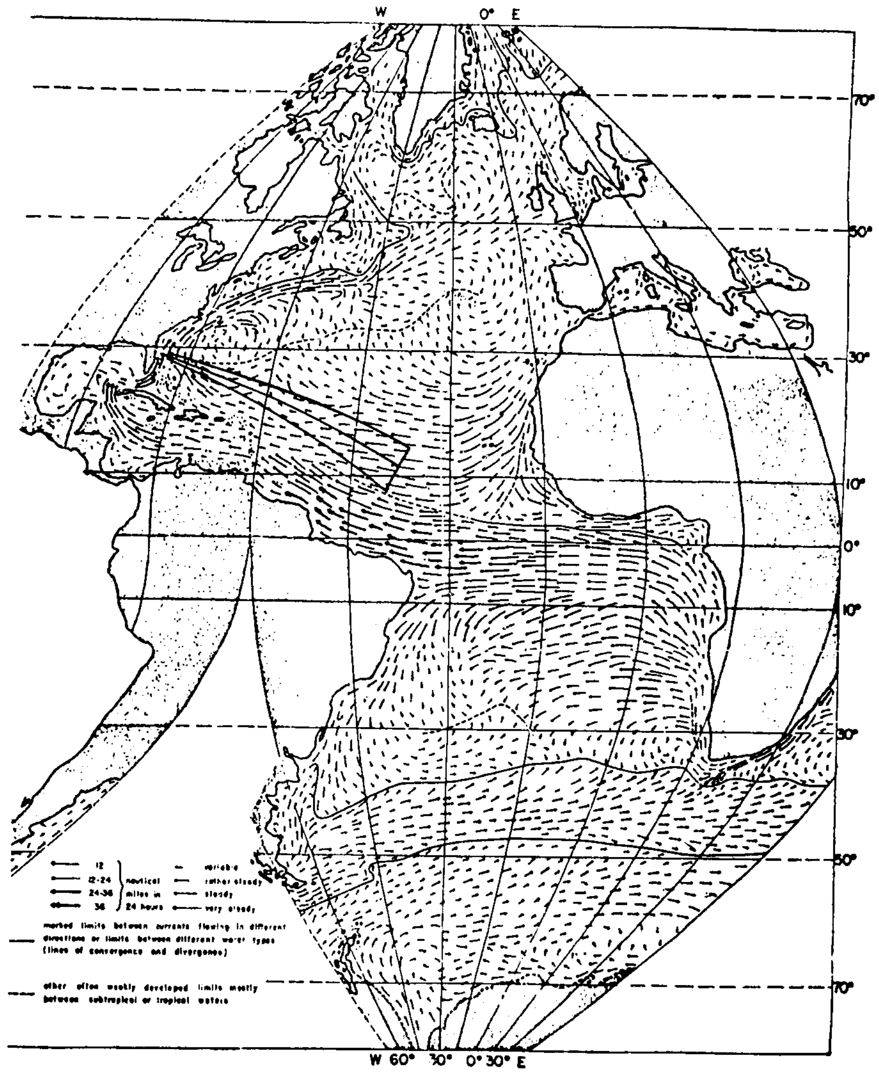

Figure II-21
Winter Surface Current Patterns[29] With Trajectory Overlay

The superimposed trajectory in Figure II-21 indicates the general pattern of surface currents in winter[29] along the selected flight paths. Summer surface current patterns[29] are shown in Figure II-22. A profile of the bottom along the 100° launch azimuth path is presented in Figure II-23. From these curves it may be noted that, at any distance greater than about 200 miles from the Cape Canaveral area, heavy material would sink into deep waters. Surface currents in these areas are westbound and long travel times are required for surface waters to reach areas in which humans could be affected. Rapidly settling fragments and even smaller fragments (less than 1 mm) should be removed, in large proportion, from the human food chain before significant fishing areas of any nation are reached.

Fisheries in the area are indicated in Figure II-24,[30] again with a trajectory pattern superimposed. It can be seen from this data that beyond the Blake Escarpment no significant fishing industry appears to exist. There remains a question (not likely to be answered in the near future) as to whether the area in which impact is likely is a breeding, or feeding area for fish which are caught in areas of the ocean closer to shore.

3. Meteorology

One of the better references on general meteorological conditions in the downrange area is the Marine Climatic Atlas of the World, Volume 1, North Atlantic Ocean, published by the U. S. Navy.[31] Data in these areas are sparse, particularly along the intended flight paths where few, if any, permanent weather stations exist. Charts in the Marine Atlas cited above do present data classified by month covering surface and upper air winds, temperature, ceiling and visibility, etc. Perhaps the most pertinent of these are the surface wind roses, an example of which is reproduced from this source as Figure II-25. Such data may be useful in preliminary plans for establishing the stations for tracking vessels during a test firing, but actual weather observations immediately prior to the launch would be preferable.

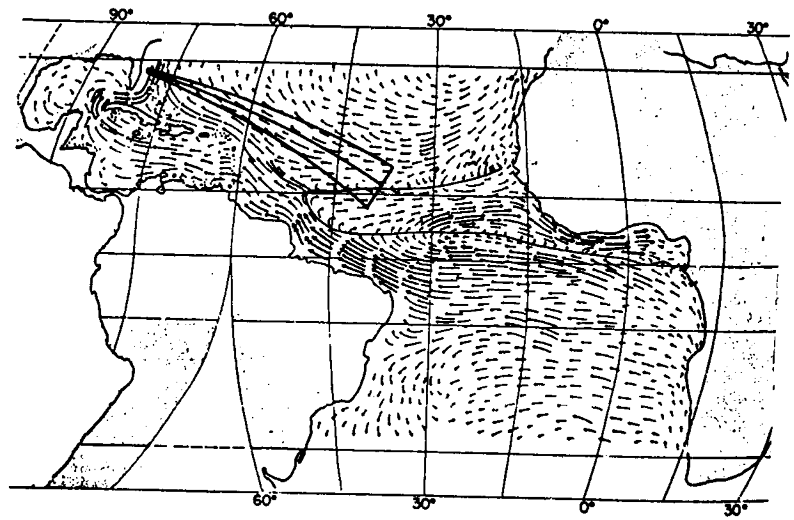

Figure II-22

Summer Surface Current Patterns[29] With Trajectory Overlay

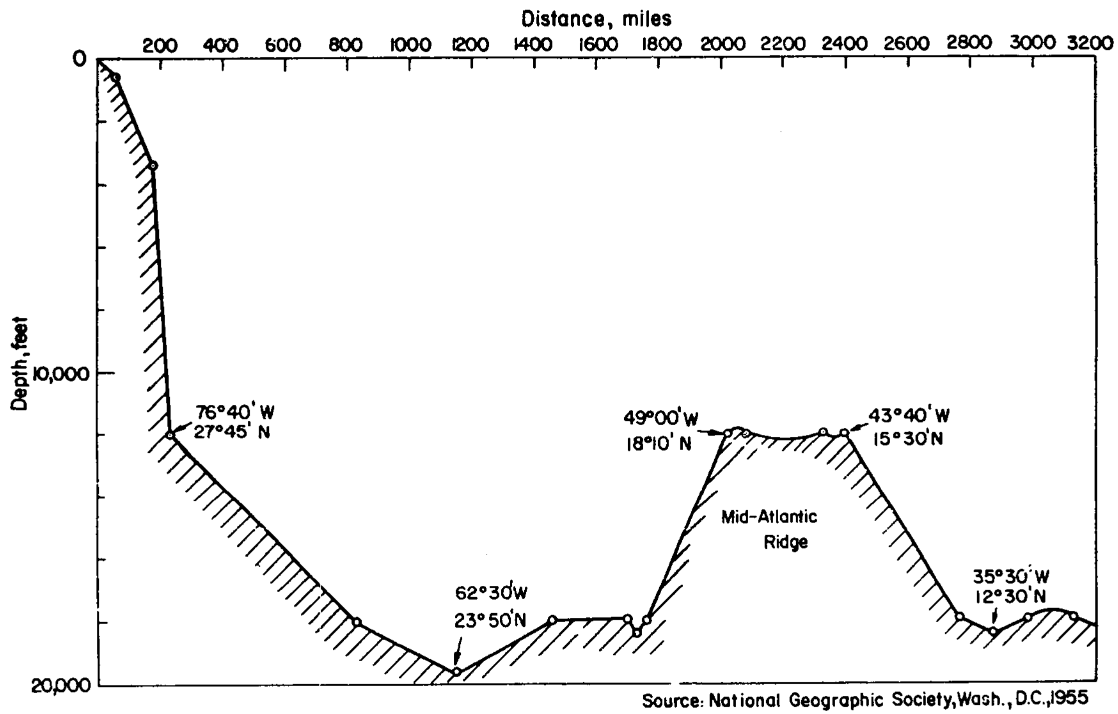

Figure II-23
Bottom Profile Along RIFT Trajectory

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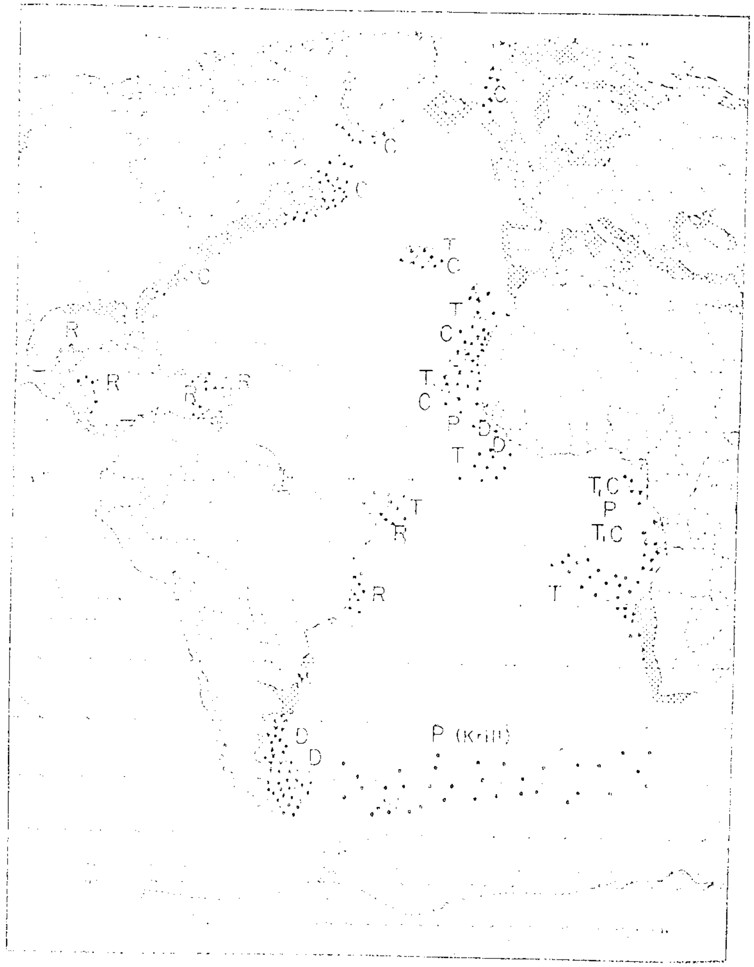
NATURAL BASES OF FISHERIES IN THE ATLANTIC OCEAN



Present exploitation [illegible] in the Atlantic Ocean

[illegible]

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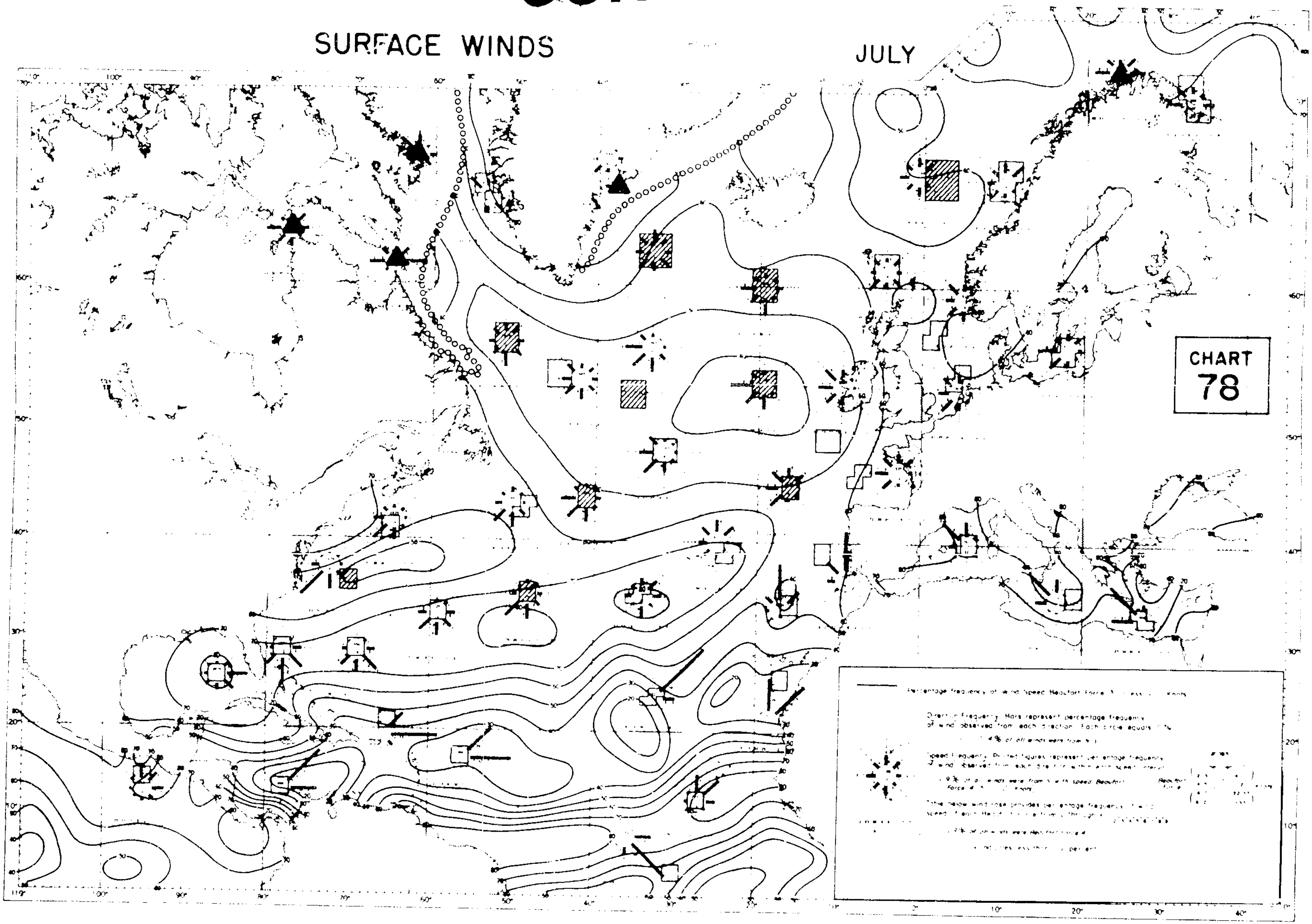

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4. Population Data

Estimates of population for downrange landmasses are presented in Table II-7.[16,32] It is apparent that the major population concentrations are in Cuba, Haiti, the Dominican Republic, Puerto Rico, and Jamaica.

TABLE II-7

DOWNRANGE - LAND MASSES - 1960 POPULATION [16,32]

	Population	
Bahama Islands (U.K.)	136,000	
Cuba	6,627,000	
Jamaica	1,537,000	
Haiti	3,492,000	
Dominican Republic	2,929,000	
Puerto Rico (USA)	2,350,000	
Leeward Islands - Lesser Antilles		(Approximately 458,000)
Virgin Islands (USA)	32,000	
Virgin Islands (U.K.)	8,000	
Anguilla	7,900	
St. Kitts	33,600	
Nevis	14,000	
Antigua	50,000	
Montserrat	1,400	
Guadeloupe	251,000	
Dominica	60,000	
Windward Islands - Lesser Antilles		(Approximately 767,000)
Martinique	258,000	
St. Lucia	86,000	
Barbados	227,000	
St. Vincent	75,000	
Grenada	86,000	
Tobago	34,000	
Trinidad	686,000	
Cape Verde Islands	148,000	
Bermuda (U.K.)	44,000	

III. ENVIRONMENTAL TRANSPORT AND DOSE CALCULATION MODELS

A. AIRBORNE CONTAMINANTS

1. Atmospheric Transport Models

The transport and dispersion of pollutants in the atmosphere has been a subject of study for some time. The development of the atomic energy industry with its concomitant radioactive waste gases, and the growing concern about air pollution from all sources and its effect on health by the public and professional people has led to an increased study of the dispersal characteristics and capabilities of the atmosphere. As a result of this interest, a considerable amount of theoretical and experimental work on atmospheric dispersal has been undertaken within the past fifteen years.

There are many analytical relationships presented in the literature for computing the concentration of a material downwind of a source as a function of the various meteorological parameters involved. Among these are the classic equations of Sutton,[33] and the relationships presented by Couchman,[34] Haugen, et al.,[8] and Pasquill.[12] Sutton's equation has been widely used in the atomic energy industry[35] and it enables a number of useful derivations to be made. The basic form for the cloud centerline concentration downwind from a ground level point source is:

$$\chi(x) = \frac{2Q}{\pi C_y C_z \bar{u} x^{2-n}} \qquad \text{(III-1)}$$

where:

$\chi(x)$ = ground level concentration at x, units/m^3
Q = source strength, units/sec.
C_y, C_z = diffusion coefficients in the y & z directions, meters $^{n/2}$
n = a turbulence parameter
$\bar{u}$ = mean wind speed, meters/sec.
x = downwind distance, meters.

A similar relationship was derived by Couchman from experimental data, and can be written in the form:

$$\chi(x) = \frac{Q}{\pi C_y C_z \bar{u} x^{m_y + m_z}} \qquad \text{(III-2)}$$

where: m_y, m_z, C_y, C_z are experimentally fitted diffusion parameters.

Based on a portion of the same data as the previous relationship, the prediction equation presented by Haugen, et al., takes the form:

$$\chi(x) = \frac{KQ}{\sigma(A)^b \, x^a} \qquad \text{(III-3)}$$

where: $\sigma(A)$ = standard deviation of azimuthal wind direction, degrees

k, a, b = empirically derived constants for each stability pattern

The last formulation, and the one used in this study, is that presented by Gifford [36] derived from the work of Pasquill [12] and Meade. [37] This formulation of the continuity equation is expressed as:

$$\chi(x,y) = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp - \left[\frac{y^2}{2\sigma_y^2} + \frac{h^2}{2\sigma_z^2} \right] \qquad \text{(III-4)}$$

where: σ_y, σ_z = dispersion parameters representing the Gaussian standard deviation of cloud concentration, in the $\underline{y}$ and $\underline{z}$ directions, meters

h = height of emission above the ground, meters

y = lateral, or crosswind, distance from plume centerline, meters

exp { } = correction for elevated releases, or off-centerline concentrations

Values of σ_y and σ_z have been presented by Hilsmeier and Gifford [38] in graphic form as a function of $\underline{x}$, based on the work of Pasquill and

Meade which derive from standard meteorological observations and observation of dispersion under the various conditions of stability. In order to provide a basis for comparison of the several dispersion equations, values of $\chi\bar{u}/Q$ were calculated for the inversion condition using each of the four relationships described above. Values of the diffusion parameters appropriate to each equation for the inversion were used, and the results plotted in Figure III-1 as a function of downwind distance. For Sutton, $\underline{n}$ = 0.5, C_yC_z = 0.01; for Couchman, C_y = 0.44, C_z = 0.20, m_y = 0.69, m_z = 0.73; for Haugen, K = 73.65, $\sigma(A)$ = 3, $\underline{a}$ = 1.38, $\underline{b}$ = 1.528; and for Pasquill, σ_y and σ_z for class "F". From Figure III-1, it may be noted that the dilution factors at a given distance vary by about an order of magnitude from maximum to minimum, and that the Pasquill correlation is about the closest to the average.

2. Selection of Meteorological Parameters

As stated above, the Pasquill formulation was used in this study. However, several parameters must be selected for use in the dispersion equation in order to put a reasonable limit on the infinite number of possible meteorological situations. These selections should encompass the range of conditions possible in an accident situation, with a bias toward the least favorable conditions. The selections to be made are the stability classes, and the wind speeds. It should be recognized that the derivation of the downwind concentration at a point finds its greatest usefulness when applied to continuous releases. Puff releases, which are the only kind considered in this report, cannot be predicted with the same degree of confidence as extended releases, since the puff, as it moves downwind, may depart radically from the behavior and direction of movement expected for a continuous release. However, for the purposes of this study, the parameters developed by Pasquill have been assumed to apply to the puff case. It would be highly desirable in the near future to obtain an indication of the behavior of puffs released at the Cape Canaveral area.

Data presented in Section II-5 for the Cape Canaveral area indicate that the median minimum wind speed for daytime and nighttime periods varied with the wind direction; that stable conditions predominate at night with some incidence of neutral conditions; and that neutral and lapse conditions prevail during the daylight hours. For this study the

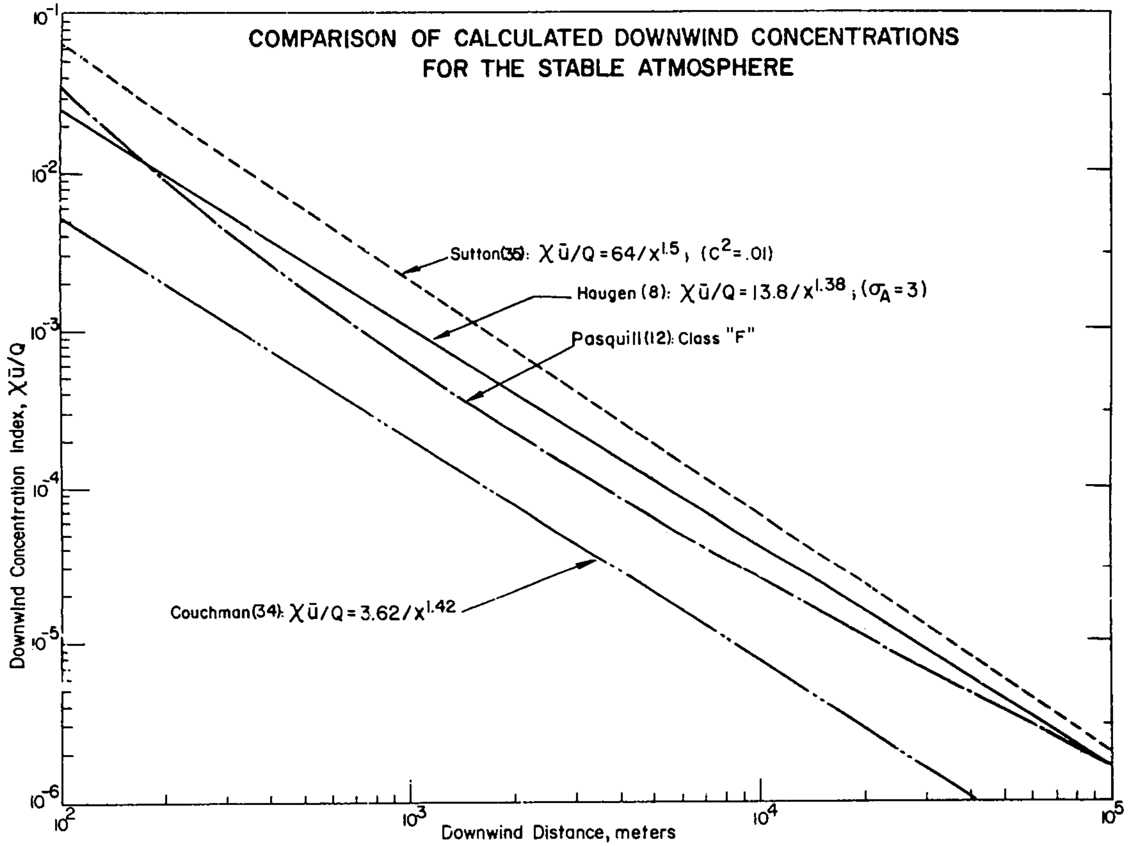

COMPARISON OF CALCULATED DOWNWIND CONCENTRATIONS
FOR THE STABLE ATMOSPHERE
Sutton(35): $\chi\bar{u}/Q = 64/x^{1.5}$, ($C^2 = .01$)
Haugen (8): $\chi\bar{u}/Q = 13.8/x^{1.38}$; ($\sigma_A = 3$)
Pasquill (12): Class "F"
Couchman(34): $\chi\bar{u}/Q = 3.62/x^{1.42}$
Downwind Concentration Index, $\chi\bar{u}/Q$
Downwind Distance, meters
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^2
10^3
10^4
10^5

Figure III-1

following conditions were specified: for the daytime, Pasquill's moderately unstable (B) and neutral (D) stability conditions with daytime surface winds to the south and west of 2.8 meters per second; for nighttime conditions, the neutral stability (D) and moderately stable (F) cases were evaluated with wind speeds of 1.3 meters per second to the south and 2.8 meters per second to the west.

In the analysis by the U. S. Weather Bureau of stability conditions at Cape Canaveral on the basis of standard meteorological observations reported in Section II-5, a very stable pattern (designated F^+ or G) is noted to have an appreciable frequency of occurrence under nighttime conditions. It was not adopted for consideration in this study since no dispersion parameters are provided in the work of Pasquill or Gifford for this condition, and since estimation of dispersion parameters would add another uncertainty to the analysis. For the purposes of this preliminary evaluation, it was felt that the use of Pasquill's Class F (moderately stable) condition would be sufficient to define the significance of the inversion stability pattern to the over-all hazard problem.

3. Dose Computation Models

Doses deriving from radioactive materials released to the atmosphere will depend upon the fractionation of the material into gases and particles of various sizes and the mode of dose delivery to the body, as well as on the diffusion and dispersion of material in the atmosphere.

The physical characteristics of such releases will depend upon the amount and rate of fission or chemical energy input to a reactor system and its mechanical properties. The transport of released materials will vary greatly with their state and/or particle size. Neglecting chemical effects, gases and sub-micron and micron-sized particles of moderate density will be transported alike; that is, particles less than about 10μm will tend to be suspended by vertical turbulence in the atmosphere, and will diffuse similarly to gases. Larger particles will tend to be removed from the cloud by sedimentation at rates which depend on their size, shape and density. These larger particles also are not readily respirable, and would create external rather than internal radiation dose problems.

Several modes of radiation dose delivery are engendered by the air transport of radioactive materials. These include the external whole body gamma dose to a person immersed in the passing cloud; the internal doses following inhalation of material from the passing cloud; the irradiation of individuals standing on a surface contaminated by deposition from the passing cloud; and the ingestion of food or water contaminated by deposition from the cloud. Each of these sources of dose is considered in the sections which follow.

a. Cloud Depletion

One of the more significant factors affecting the downwind doses is the deposition of material from the cloud on the ground. This depletion of the cloud not only decreases the exposure downwind, but also produces the surface radiation problem which remains after the cloud has passed.

Deposition from the cloud is normally treated by using a "deposition velocity" which takes into account all the factors which affect the loss of material from the cloud onto foliage and ground surfaces under dry (no precipitation) conditions. These factors include chemical reactions and sorption, as well as gravitational settling. Values for the deposition velocity of several elements have been reported in the literature. Chamberlain (39) has reported deposition velocities for iodine of 0.3 to 0.5 cm/sec on vegetation following the Windscale accident; Islitzer (40) has used a deposition velocity of 0.2 centimeters per second in computing the amount of iodine released during the course of the SL-1 accident at the National Reactor Testing Station. Healy (41) has reported a similar value under field experimental conditions at another part of the NRTS. Vegetation at NRTS is sparse; the area tends toward desert-like in its vegetation, except in irrigated areas. The range of values for iodine deposition has been reported (42) to range from approximately 0.2 to 2.5 centimeters per second. Considering the high density of foliage and humid conditions in the Cape Canaveral environment, a deposition velocity of 1 centimeter per second was adopted in this study for halogens and 0.1 centimeter per second for other volatile fission product elements. The numerical effects of these assumptions is presented in Section IV.

Gifford (43) has indicated the application of the generalized Gaussian dispersion formula to a number of specific problems associated with downwind hazard evaluation, including depletion of the cloud by dry

deposition. The derivation of the depletion correction for dry deposition follows for a ground level release (after Gifford):

$$\omega(x,y) = v_g \, \chi(x,y,o) = \frac{v_g Q_x \, e^{-y^2/2\sigma_z^2}}{\pi \sigma_y \sigma_z \bar{u}}$$

where: $\omega(x,y)$ is the surface deposition at (x,y), C/m^2; v_g is the deposition velocity, m/s; and Q_x is the residual source at $\underline{x}$ meters downwind.

The depletion of the source per unit distance is given by:

$$\frac{\partial Q_x}{\partial x} = - \int_{-\infty}^{\infty} \omega(x,y)\, dy = -\sqrt{\frac{2}{\pi}} \frac{v_g Q_x}{\bar{u} \sigma_z(x)}$$; and rearranging,

$$\frac{dQ_x}{Q_x} = -\sqrt{\frac{2}{\pi}} \frac{v_g}{\bar{u}} \frac{dx}{\sigma_z(x)}$$

Integrating with an initial condition that $Q_x = Q$ at $x = O$, gives

$$Q_x = Q \exp \left[-\sqrt{\frac{2}{\pi}} \frac{v_g}{\bar{u}} \int \frac{dx}{\sigma_z(x)} \right] \qquad \text{(III-5)}$$

Since no explicit analytical relationships are available for σ_z as a function of $\underline{x}$, the integral was evaluated numerically from values of σ_z read from the graph in Hilsmeier and Gifford. (38) To evaluate the integral from zero to 100 meters, for which no values of σ_z are plotted, the curves were extrapolated, and from the equations of these lines, the integrals were evaluated analytically. The values of the integral so obtained are plotted in Figure III-2.

With these, depletion of the cloud under dry conditions can be calculated for the chosen stability cases, wind speeds and deposition velocities. Values of Q_x/Q as a function of downwind

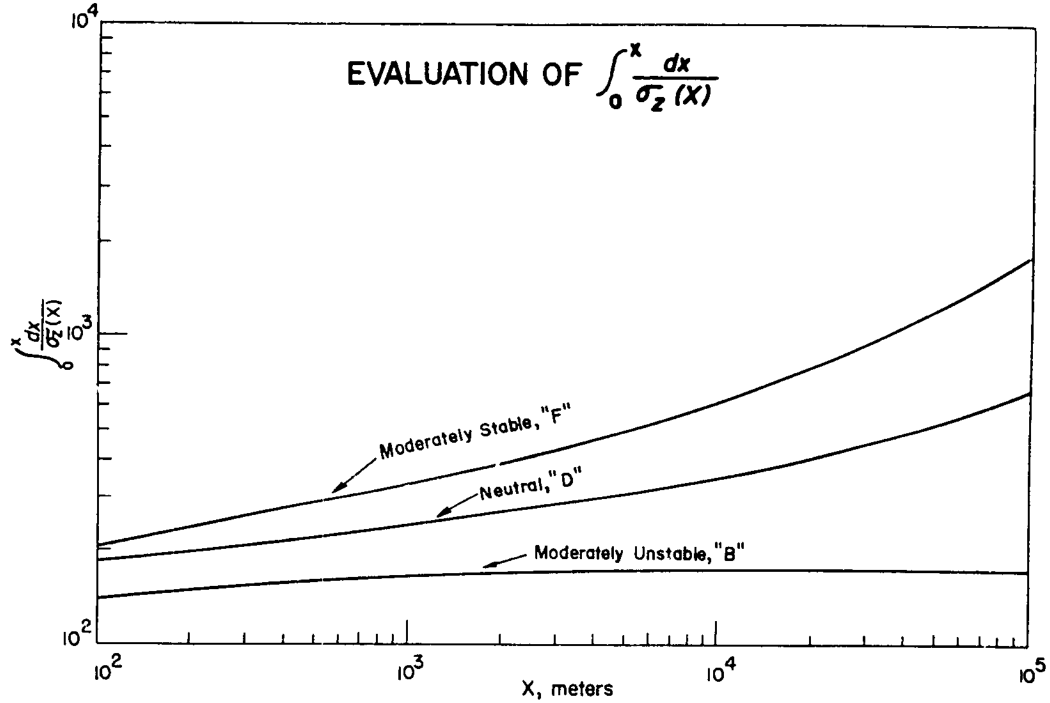

EVALUATION OF $\int_0^x \frac{dx}{\sigma_z(X)}$
10^4
10^3
10^2
$\int_0^x \frac{dx}{\sigma_z(x)}$
Moderately Stable, "F"
Neutral, "D"
Moderately Unstable, "B"
10^2
10^3
10^4
10^5
X, meters

Figure III-2

distance are presented in Figure III-3 for a deposition velocity of 10^{-2} meters/second, and the classes of stability and wind speed selected in the previous section. These values, and those computed for non-halogens (10^{-3} m/s) are used to correct the source in all subsequent dose calculations. The effect of deposition assumptions on the various doses are indicated in Section IV.

b. Cloud Doses

Direct doses during cloud passage were calculated using the method of Gammertsfelder and Waterfield,[44] modified by replacing Sutton dispersion coefficients by the equivalent σ_y and σ_z values. The relationship used by Gammertsfelder and Waterfield for centerline gamma doses from an instantaneous ground-level release is:

$$D_\gamma = (4GQ_\gamma \mu_a' \mu/\bar{u})\,(I_1 + KI_2) \text{ rads} \qquad \text{(III-6)}$$

where

G = dose conversion constant ($6.83 \frac{\text{rad-meter}^3}{\text{Watt-sec.}}$).

Q_γ = total gamma power released, watts

μ_a' = linear energy absorption coefficient for air at STP, m^{-1} ($4 \times 10^{-3}\ m^{-1}$ for 0.7 Mev γ)

μ = total linear attenuation coefficient of air corrected for temperature and pressure, m^{-1}

$\bar{u}$ = mean wind speed, m/sec.

I_1, I_2 = direct and scattered dose integrals, dimensionless

K = $(\mu' - \mu_a')/\mu_a'$, dimensionless

μ' = total linear attenuation coefficient of air at STP, m^{-1} ($9.7 \times 10^{-3}\ m^{-1}$ for 0.7 Mev γ)

I_1 and I_2 are functions of μa (where a equals $(2\sigma_y\sigma_z)^{1/2}$) evaluated in the reference.

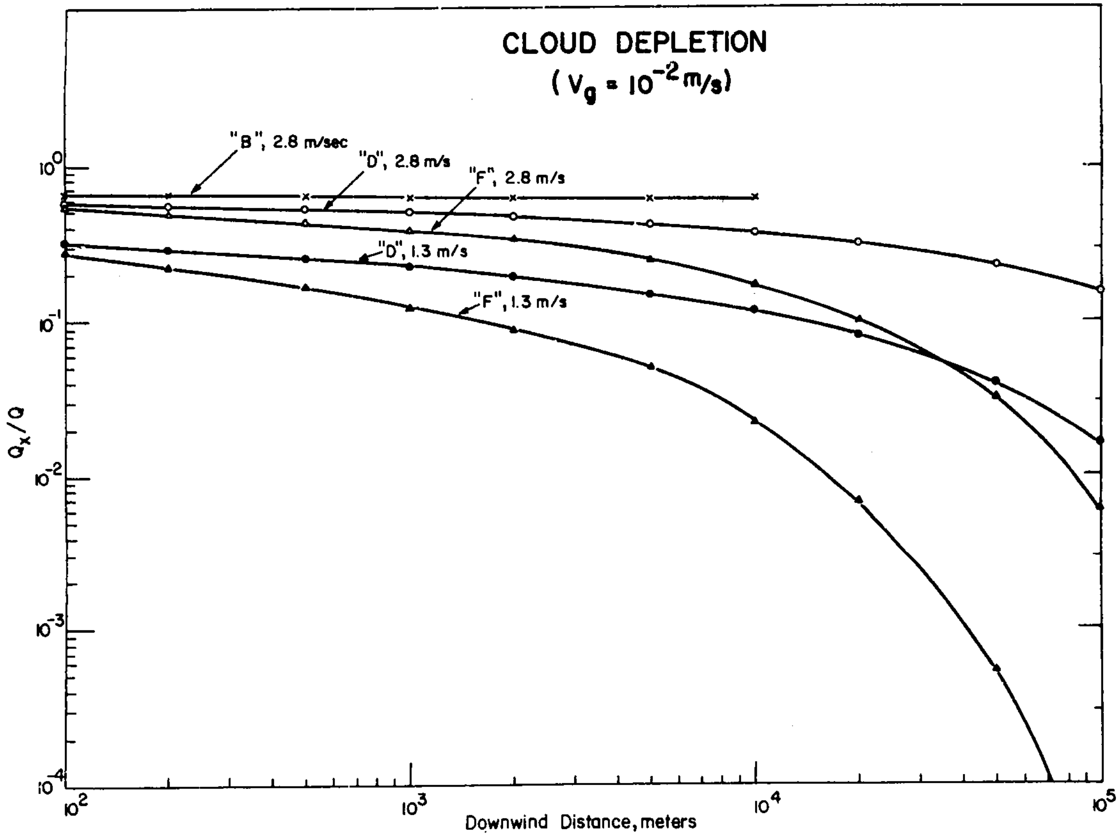

CLOUD DEPLETION
($V_g = 10^{-2}$ m/s)
"B", 2.8 m/sec
"D", 2.8 m/s
"F", 2.8 m/s
"D", 1.3 m/s
"F", 1.3 m/s
Q_x/Q
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^2
10^3
10^4
10^5
Downwind Distance, meters

Figure III-3

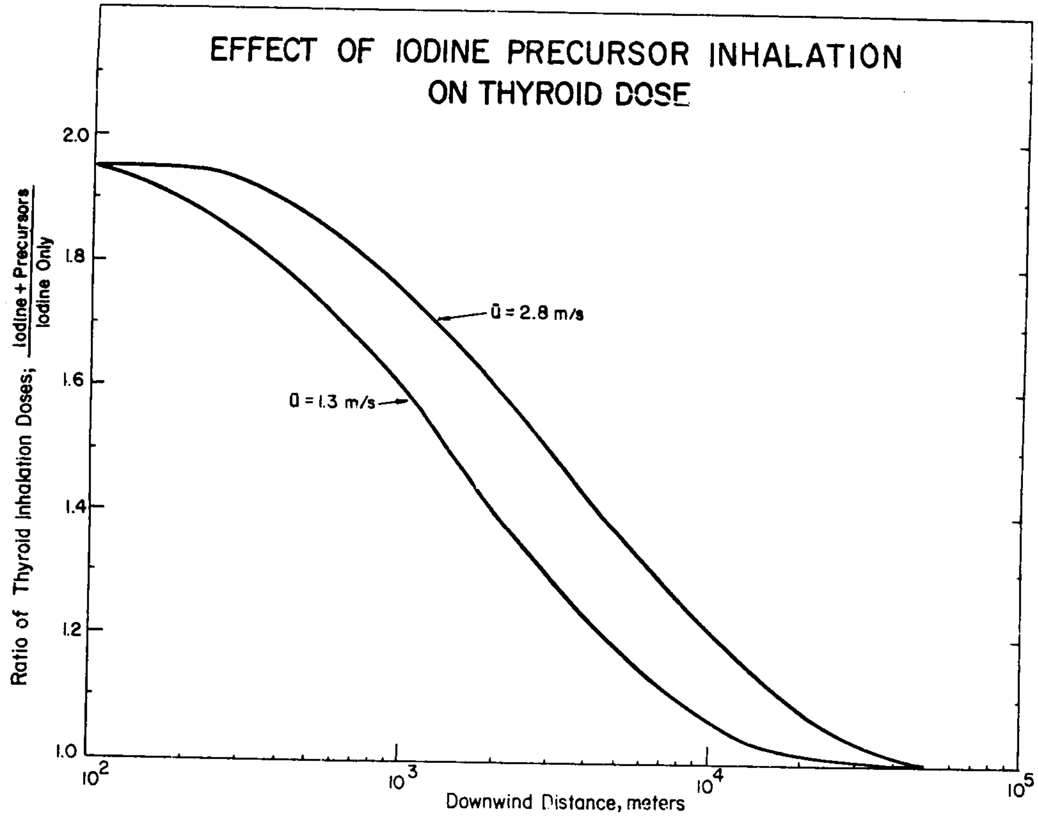
It should be recognized that this approach treats an instantaneous point source, and that values of σ_y /and σ_z are based on continuous point source data. Unfortunately there are almost no instantaneous source data available from field experiments.

c. Inhalation Doses

The inhalation dose is determined by computing the total integrated exposure ($\int \chi dt$) at downwind point and determining the product of this integrated exposure value, the breathing rate of an individual at this point and the dose per inhaled unit of activity. For an instantaneous point source, the equation for total integrated exposure (in curie-seconds per cubic meter) is the same in form as Equation (III-4) with the modification that Q in the instantaneous case is a total amount of material released rather than a rate-of-release as in the continuous case.

For an adult the breathing rate used as representative of the standard man is ten cubic meters per eight hours of active time and ten cubic meters for the remaining sixteen hours. Since a release of material is liable to occur at any time, the higher or active breathing rate is used, approximately 3.5×10^{-4} cubic meters per second. The dose per inhaled curie is derived from current ICRP[45] biological and physical values.

It has been indicated [46,47] that by far the most critical internal dose, where volatile fractionation of fission products occurs, is the thyroid dose due to iodine, and therefore this is the only nuclide so treated in this study. In the case of iodine, the question of inhalation of volatile precursors is of some importance, since most of the iodines do not reach their peak activities unt several hours after an excursion. The assumption that the precursors of iodine (which are also volatile) are not inhaled results in doses which are lower by a factor ranging up to 2, than those which are calculated assuming the inhalation of iodine precursors and their subsequent growth into iodine in the body. There is essentially no data on the route in the body of iodine formed in vivo, although the selectivity of the thyroid for iodine would lead to the judgment that it is rapidly transported to that organ. Since relatively long-lived iodine precursors (notably Te-132) have been detected at distances up to 35 miles from KIWI B-1A test,[48] this analysis assumes the inhalation and retention of iodine precursors. The effect of this assumption on dose is indicated in Figure III-4.



EFFECT OF IODINE PRECURSOR INHALATION ON THYROID DOSE
Ratio of Thyroid Inhalation Doses; Iodine + Precursors / Iodine Only
2.0
1.8
1.6
1.4
1.2
1.0
Ū = 2.8 m/s
Ū = 1.3 m/s
10^2
10^3
10^4
10^5
Downwind Distance, meters

Figure III-4

As mentioned in Section 3.a above, another significant factor affecting thyroid dose is the assumption made of iodine deposition velocity. As indicated in Figure III-3, calculated cloud depletions are large with a deposition velocity of 0.01 m/s, particularly in the moderately stable atmosphere, thereby markedly reducing inhalation doses at large distances.

d. Deposition Doses

Having considered the doses resulting from whole body exposure during cloud passage, and from inhalation of material contained in the cloud, the final doses to be considered are those resulting from the deposition on foliar and ground surfaces of material contained in the cloud, assuming that all material is present as gases or as particulates which are so fine that they behave as gases. Sources to be considered in the deposition case are those resulting from both dry deposition and from rainout. In the first case, the significance of the deposition velocities assumed is obvious. If one assumes zero deposition velocity, the residual surface contamination is also zero. On the other hand, cloud inhalation and direct doses are considerably higher, particularly at larger distances since no cloud depletion occurs. In order to provide for a consistent approach to the problem, the same deposition velocities have been used to compute both inhalation and direct cloud doses and the concentrations resulting from the dry deposition of material from the cloud.

1) Direct Radiation

To determine the radiation doses resulting from deposited material, the fraction, deposited in successive distance intervals was assumed to be uniformly distributed over n circles of radius $2\sigma_y$ where n equals the interval divided by $4\,\sigma_y$. The value of σ_y used is that for the average distance of the interval under consideration. The relationship for dose rate on the axis of a disc source is used for determining the dose rate at a distance of one meter of the surface [49]:

$$R_{\gamma s} = \frac{q\Gamma}{4\sigma_y^{\,2}} \ln \left(1 + 4\,\sigma_y^{\,2}/h^2\right) \text{ rads/hr} \qquad \text{(III-7)}$$

where q = total gamma power distributed over a circle of radius $2\sigma_y$,

$$= \frac{Q_Y\left[(Q_x/Q)_{x_1} - (Q_x/Q)_{x_2}\right]}{\pi\sigma_y\,(x_2 - x_1)} \text{ watts}$$

Γ = dose rate from a point source at unit distance ($100\ \frac{\text{rad-m}^2}{\text{hr-watt}}$ for 0.7 Mev γ)

h = height on axis above disc, meters

This relationship neglects buildup from air scattering, and therefore tends to underestimate the dose to some extent. However, it is felt that this error is small compared to those introduced by variations in deposition caused by local foliage or ground surface characteristics.

2) <u>Ingestion</u>

Air transport of radioactive material also produces contamination of land and water areas off-site which may reach man via the food chain. As indicated previously, dry deposition is calculated as the product of the integrated concentration at a given point and the deposition velocity. As deposition velocity increases, the total deposition may increase or decrease. This occurs since on the one hand an increase in deposition velocity increases the deposition rate at a point but also decreases the inventory of material reaching that point due to prior depletion of the cloud. On the other hand, a lower deposition velocity may actually increase the amount of material deposited since it permits a less depleted cloud to reach the point in question.

Again, iodine provides the major source of concern with respect to deposition of radioactive material on land. Iodine is particularly important where foods are produced for which the transit time to man is very short, as for example, fresh milk or water. Those dietary items in which biological intermediaries play a significant role (as, for example, the cow) are discussed in Section III-C, below. This section will be concerned with

deposition in surface water supplies of iodine and the bone seekers, strontium and barium, and development of the dose model for acute intake exposures.

For a single intake, the dose to an organ is given by:

$$D_t = \frac{8.54 \times 10^2}{m}\, A f \bar{E} T_e \left(1 - e^{-.693t/T_e}\right) \text{ rads} \qquad \text{(III-8)}$$

where D_t = integrated dose at <u>t</u> seconds, rads

m = mass of the organ, grams

A = ingested activity, curies

f = fraction of ingested activity reaching the organ

$\bar{E}$ = effective energy, Mev/disintegration

T_e = effective half-life, seconds

For Iodine-131, considering a child as the limiting individual, values of these constants are: $m = 2$, $f = 0.3$, $\bar{E} = 0.22$, $T_e = 6.57 \times 10^5$. For a dose of 1.5 rad in a year as recommended by FRC(50), a value of $A = 8.1 \times 10^{-8}$ curies is obtained.

A similar exercise may be conducted for Strontium-89 and -90, and Barium-140, using the FRC recommendation of 1.5 rem per year to the bone of an adult. These yield acute intake values of 4.8 μc, 1.15 μc, and 90μc, respectively.

Exposure may not be restricted to that resulting from single intakes, however, but may result from continued intake of a decaying source (single deposition event). In this event, the acceptable intake on the first day can be calculated assuming the total activity ingested (or inhaled), and the resulting integrated dose, are the same as the single intake case. The intake per day is:

$$a(t) = a_1 e^{-\lambda t}$$

where $a(t)$ = daily intake after <u>t</u> days, curies/day,

a_1 = intake on first day.

The total intake is then $\int_0^\infty a(t)\,dt = a_1/\lambda$, which must be equal to the single intake, A. Therefore, the initial daily intake which, if continued, would result in the same integrated dose as a single intake of A curies, is $A\lambda$. Since $\lambda = .693/T_{1/2}$, $a_1 = A/1.44\,T_{1/2}$.

On this basis, acceptable initial intake rates are

for I-131; $0.081\,\mu c/1.44 \times 8.05$ days = 0.007 μc/day

Sr-89; $4.8\,\mu c/1.44 \times 50.5$ days = 0.066 μc/day

Sr-90; $1.15\,\mu c/1.44 \times 10^4$ days = 8×10^{-5} μc/day

Ba-140; $90\,\mu c/1.44 \times 12.8$ days = 4.9 μc/day

In the case of Sr-90, however, since both the physical and effective half-lives are so long it seems more reasonable to use the FRC derived Intake Guide of 200 $\mu\mu c$ ($2 \times 10^{-4}\,\mu c$)/day.

On the basis of present plans for water usage, drinking water contamination appears to be an unlikely source of activity exposure from an accident in the vicinity of the launch site, since most water supplies derive from ground water sources, as indicated in Section II-A.6. However, Lake Washington (about 55 kilometers SSW of the launch site) is at present a drinking water supply for the City of Melbourne. Additionally, the City of Cocoa is presently considering Lake Poinsett (about 40 kilometers SW of the launch site) as a source of drinking water. As indicated in Section IV.C. dry deposition or deposition by precipitation can introduce a significant amount of activity at these distances.

To compute the concentration in such surface waters in the absence of knowledge of their hydraulic mixing and sediment characteristics, the assumption is made that material deposited on the surface is diluted by only the top ten centimeters. Thus, the amount deposited per square meter is divided by 10^5 cm^3 to provide an estimate of the concentration.

A second form of introduction of activity in the drinking water supplies would be by deposition on the ground with subsequent washing down of the material into the non-artesian ground water

table and removal in shallow wells. Since the production of long half-life materials in an excursion is relatively small, the delay afforded by the ground water leaching process would appear to provide considerable opportunity for decay of shorter-lived materials prior to the withdrawal of water from ground water sources. An additional protective feature would derive from whatever ion exchange capacity exists in the local soils.

The velocity of the non-artesian ground water can be derived from a consideration of the permeability of the sediments through which the water flows, and the hydraulic gradient. The coefficient of permeability has been reported (2) as 300 gallons per square foot per day. The same study indicates hydraulic gradients ranging from about 70 feet per mile at the Indian River to about 1 foot per mile at the St. Johns River marsh. Assuming an average value of 10 feet per mile, the velocity of ground water corresponding to this gradient would be

$$\frac{300\text{ gal.}}{\text{ft}^2\text{- day}} \times \frac{10\text{ ft}}{\text{mile}} \times \frac{1\text{ ft}^3}{7.48\text{ gal}} \times \frac{1\text{ mile}}{5280\text{ ft}} = 0.076\text{ ft/day}$$

Over the range of hydraulic gradients observed, the velocities would vary from a minimum of less than 0.01 feet per day in the marsh areas to a maximum of less than 0.6 feet per day at the Indian River shoreline, if the permeability coefficient is reasonably constant.

As an initial approximation, concentration estimates could be derived from the assumptions, (a) that the material deposited per square meter is diluted by one month's rainfall (average about 4 inches, or 10 cm), and (b) that, on the average a decay period of at least 15 days occurs between deposition and consumption. Until better information is available with respect to this latter point, and data are available on ion-exchange capacity of the soil these assumptions seem temporarily acceptable. In any event, this mode of dose delivery appears much less significant than that from surface water contamination due to the delay and to the sorption of contaminants on soil.

e. Large Particle Fallout

Another source of radiation exposure would result from the transport of particles of significant size in the event of destruct or booster explosion following an excursion at some height over the launch site. Destruct of the vehicle might or might not result in a nuclear excursion; if one assumes the destruct might occur because of an excursion in the nuclear reactor, then the fragmentation of the reactor core would determine in large measure the distribution of particles on the ground. Similarly, the detonation of the booster on or above the pad would result in some distribution of reactor fragments which might or might not be active depending upon whether or not an excursion was initiated and the magnitude of the integrated power in such an excursion.

The computation of fallout patterns is extremely complex and is highly dependent upon the particle size distribution obtained as a result of the hypothesized accident. In order to provide a basic approach to this question, fallout rate computations were performed using the Patrick Air Force Base Reference Atmosphere [51] for a range of particle sizes of specific gravity 2.0. The procedure has been described by Schuert [52] and has been applied in this study to obtain the rates of fall of various size particles from altitudes up to 8,000 meters. These velocities are indicated as a function of starting altitude in Figure III-5 for irregular particles. It is possible to fit the velocity curves with an expression of the type: $V_A = V_o e^{kA}$ where V_A = terminal velocity for particles falling from altitude A; V_o is the velocity intercept at ground level; and k is a rate constant.

Values of k are: 5.3×10^{-5} for $1\ \text{cm} \geq d \geq 1\ \text{mm}$

4.2×10^{-5} for $1\ \text{mm} \geq d \geq 0.1\ \text{mm}$

1.9×10^{-5} for $d < 0.1\ \text{mm}$

With this expression for V_A, a relationship for the time of fall, t of a particle from a particular altitude can be derived:

$$t = \frac{1}{kV_o}\left(1 - e^{-kA}\right) \qquad \text{(III-9)}$$

To determine the horizontal displacement of falling particles also requires knowledge of the change of wind speed with

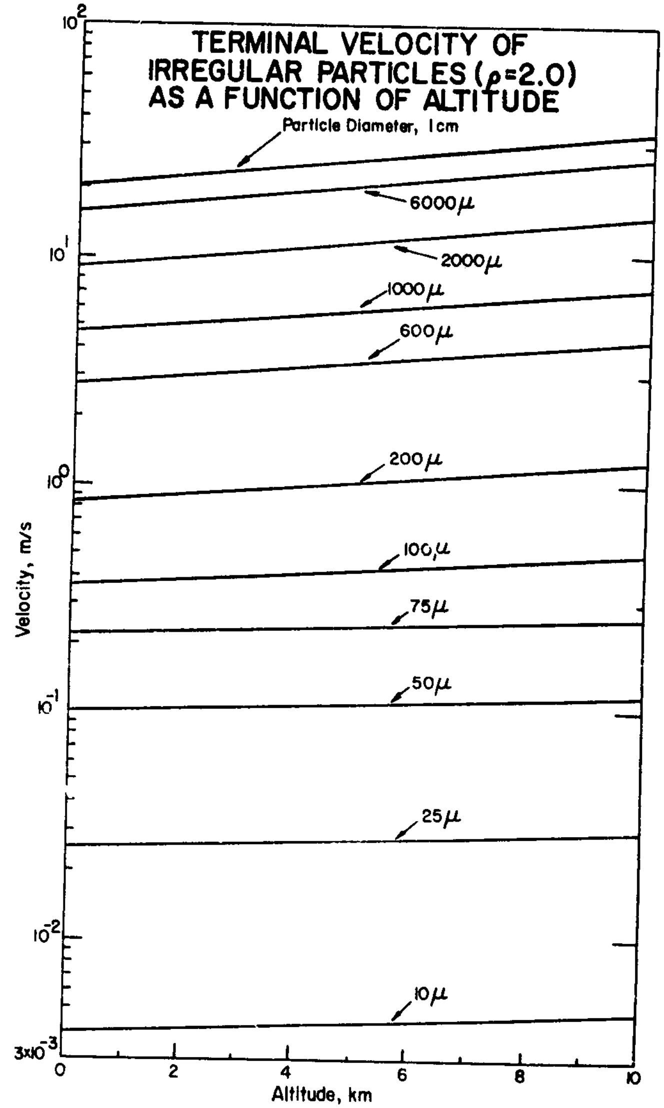


Figure III-5

altitude. The relationship adopted by the MSFC[14] for Cape Canaveral is:

$$V_A = V_S \, (A/h_S)^{0.20} \qquad \text{(III-10)}$$

where: V_A = measured surface wind speed at elevation h_S

Using the above expressions for V_A and t, it is possible to derive a relationship for the horizontal displacement of a particle. In an increment of time, dt, the horizontal displacement, dS, equals V_A dt. Substituting equations III-9 and -10 and integrating, the following expression is obtained for the horizontal displacement, S:

$$S = \frac{V_S}{V_o h_s^{0.20}} \int_o^A A^{0.20} e^{-kA} dA \qquad \text{(III-11)}$$

This expression has been solved by numerical integration for the three settling rate constants, and the results presented in Figure III-6 as $S(V_o/V_S)$ for altitudes up to 5,000 meters. Values of V_o may be taken from Figure III-5.

The next problem in determining particle fallout patterns is most critical; that is, the derivation of the particle size distribution resulting from a nuclear excursion or conventional explosive destruct or booster detonation on the reactor core assembly. The basis for estimating disruption of a graphite core following an excursion is provided by work done at LASL[53] on the feasibility of ROVER reactor disposal with high explosives. It must be recognized that the disassembly of the core by high explosive may be entirely different in character and results from that generated by an excursion or by an external explosion, due to the difference in both energy deposition timing and location. However, for the purposes of estimating the fragment size distribution, it is assumed herein that the effects of the nuclear excursion or the external explosive force are as effective as internally-deposited high explosive in disintegration of the core materials. The modified distribution law developed at LASL is:

$$F(d) = \frac{\exp - (d/R'_o)^{B'} - \exp - (R_{max}/R'_o)^{B'}}{1 - \exp - (R_{max}/R'_o)^{B'}} \qquad \text{(III-12)}$$

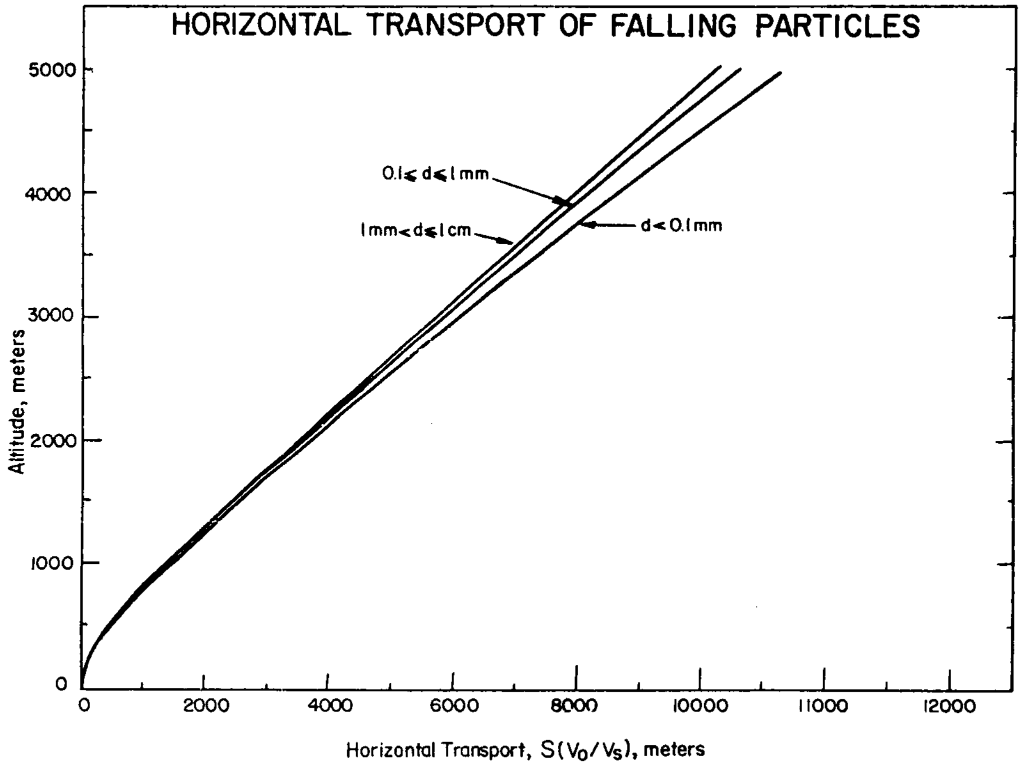

HORIZONTAL TRANSPORT OF FALLING PARTICLES
0.1≤ d≤1 mm
1 mm< d≤1 cm
d< 0.1 mm
Altitude, meters
0
1000
2000
3000
4000
5000
0
2000
4000
6000
8000
10000
11000
12000
Horizontal Transport, S(Vo/Vs), meters

Figure III-6

where: $F(d)$ = weight fraction of fragments of dimension greater than $\underline{d}$,

R_{max} = a maximum particle dimension

R'_o = a "typical" particle dimension

B' = a constant

Values assumed by LASL were $B' = 2/3$; $R'_o = 15$ millimeters; and $R_{max} = 7$, 19 millimeters for 100 pounds of high explosive. If one attempts to scale for 10 pound explosions, using the relationship indicated in the LASL report, the value of R'_o derived is greater than the maximum dimension of core material. Therefore, R'_o was set equal to R_{max}. Substituting values in Equation (III-12) for both 10 and 100 pounds of high explosive, particle size distribution curves are obtained for each assumption of maximum particle dimension (7 millimeters and 19 millimeters). Distribution curves are shown in Figure III-7 for both sizes as solid lines for the 10 pound case. Also shown on this graph as dashed lines are the results using the LASL assumptions for 100 pounds of high explosive.

It can be noted that the scaling down assumptions do not have a significant effect on the particle size distributions obtained, and that a significant fraction of the particles are small enough to be transported off-site if the release occurs at only moderate heights. For example, from Figures III-5 and III-6 it can be shown that 100 μ particles will travel greater than 17.5 km (off-site) in a 5 m/s wind if the release height is greater than about 800 meters.

With the horizontal transport data and a particle size distribution, the activity per particle completes the information necessary to estimate downwind doses resulting from such particles. For the particulates, consideration should be given to a number of dose delivery modes, such as whole body gamma dose, lung dose, GI tract dose, etc. However, a recent report by Fish and Patterson [54] on the hazards associated with re-entry of single particles, indicates that the most critical exposure may result from beta dose to skin surfaces.

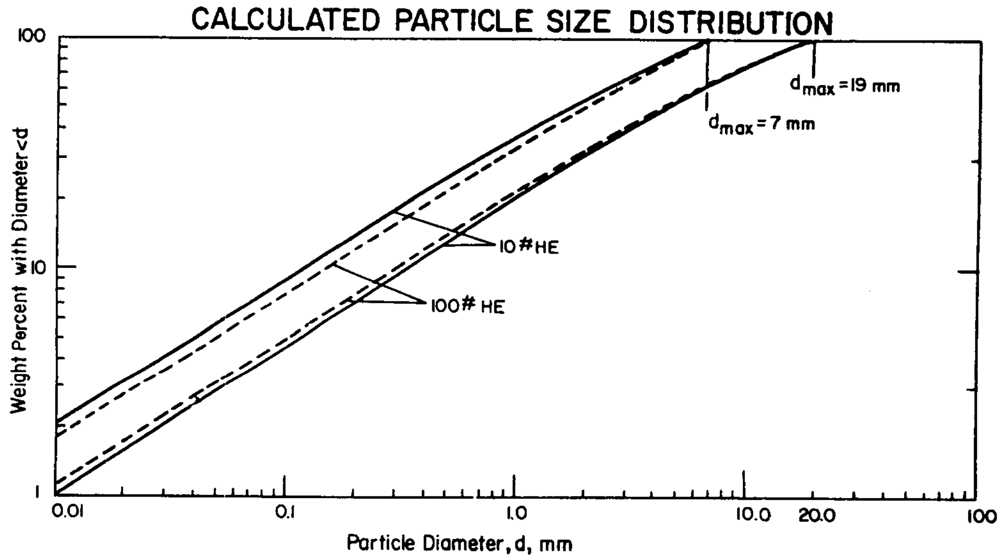

CALCULATED PARTICLE SIZE DISTRIBUTION
100
10
1
Weight Percent with Diameter<d
0.01
0.1
1.0
10.0
20.0
100
Particle Diameter, d, mm
d_{max} = 19 mm
d_{max} = 7 mm
10# HE
100# HE

Figure III-7

Beta dose determinations are less readily made than those for gamma because of the extreme dependence of the absorption process on beta energy. Since beta emission from a single nuclide encompasses a spectrum of particle energies, the dose distribution calculation is complex. Hine and Brownell (55) have presented formulations for dose distribution within and outside of spherical beta sources (Section 16-I-C, Equations 33, 34 and Figure 25) which are used in this study to obtain estimates of the surface beta dose. Typical beta energy spectra taken from the report of Fish and Patterson, for times of interest after fission are listed below, with appropriate absorption coefficients:

t, min	<Eβ max>	ν, cm^{-1}
10	3.3	9
100	2.7	11
1000	1.8	16
10,000	0.8	46

Gamma dose determinations were made by assuming a uniform source distribution over an area, although one square meter might be contaminated by only a few particles. The dose model used is the same as that presented in Equation III-7, although the area of coverage is determined by an assumed lateral spread of particles over a 15° sector.

B. WATERBORNE CONTAMINATION

1. Marine Transport Models

Considerable interest has been generated in recent years to develop satisfactory methods for the prediction of the transport by diffusion and dispersion of radioactive materials discharged to the oceans from waste disposal operations or the testing of nuclear weapons. Several approaches have been suggested and summarized in the Proceedings of the Monaco Conference on the Disposal of Radioactive Wastes in 1959, (56) the Brynielsson Report (57) to the International Atomic Energy Agency in 1960 and most recently a review of theoretical models of turbulent diffusion in the sea by Okubo (58) of the Chesapeake

Bay Institute. Shonfeld and Groen (59) have reviewed the mixing and exchange processes in the sea from which the subsequent general material was abstracted.

Transport of material in the sea varies in magnitude from Brownian movement of molecules to large scale circulations related to the ocean currents. When material is introduced into the ocean it is acted upon first by the turbulence of its own entry into the waters followed by turbulence due to tidal or other causes induced by frictional effects of the bottom and of the wind at the surface. After the material is dispersed by these forces larger scale eddies exert their influence. Large scale motions do not affect dispersable material such as clouds of dye or radioactive contaminants, which are small in comparison to the scale of the motion except by transporting the cloud as a whole. As soon as the cloud has grown to the size of these larger scale motions the cloud will be broken up into segments which will grow and be subjected to the same microscale actions again. Smaller scale motions will mix the separate parts of the original cloud with the surrounding water, tending to homogenize the entire volume.

Diffusion rates are proportional to the physical or chemical gradients of the properties concerned such as temperature or salinity differences. For molecular diffusion the rate of proportionality or diffusivity is a constant determined by the properties of the environment and the diffusing material. Constant diffusivity may be seen to prevail in cases where eddies are small as compared to the size of the cloud. Such conditions may occur in currents in shallow water where the depth restricts the eddy size and the bottom friction confines the horizontal spread. Although micro-scale or Fickian diffusion may prevail in this case (with the diffusivity independent of the distribution of the diffusing material) the diffusivity is not constant in time and space, it is anisotropic. When larger scale eddies come into play it is found that the diffusivity increases with the size of the diffusing cloud. Due to the nature of large scale movements a statistical treatment is necessary for the prediction of "local" concentrations under the mixing conditions called macro-scale diffusion.

Whatever the dependence of diffusivity $\underline{k}$ on scale $\underline{\ell}$

$$k = \text{constant}\ \ell^m$$

where $m = 0$ micro-scale or Fickian diffusion

$m = 1$ linear conditions (Joseph and Sendner, Pritchard)

$m = 3/4$ power function (Richardson, Stommel, Ozmidov)

A satisfactory differential equation must be obtained with boundary conditions suitable to the situation under study. Such an equation is (61):

$$\frac{\partial S}{\partial t} = M - S\lambda - \frac{\partial}{\partial x}(U_x + Sv_x) - \frac{\partial}{\partial y}(U_y + Sv_y) - \frac{\partial}{\partial z}(U_z + Sv_z)$$

where x,y,z = spatial coordinates

S, v_x, v_y, v_z, = statistical averages of concentration and velocity components over an ensemble of possible distributions of equal probability

U_x, U_y, U_z, = components of eddy diffusion transport vector $\bar{U}$ which is the statistical average of product of the random variations of $\bar{S}$ and $\bar{v}$.

M = rate of introduction of material into the sea per unit volume and time.

λ = radioactive decay constant.

This equation was simplified to the two dimensional symmetrical case, where the horizontal extent is very great in relation to the depth, the coefficient of diffusion is a product of the power function of the distance and a time variable, and initial condition of $S(r,t) \rightarrow M\frac{\delta(r)}{\pi r}$ at $t = 0$. The equation by Okubo is as follows:

$$S(r,t) = \frac{M}{\pi c\,(2-m)^{2c}\,\Gamma(c)\,k^c\,\psi(t)^c} \exp\left[-\frac{r^{2-m}}{(2-m)^2 k\,\psi(t)}\right] \qquad \text{(III-13)}$$

where r = radial distance

$c = 2/(2-m)$

$\Gamma(\alpha)$ = gamma function of α

$\psi(t) = \int_0^t F(t')\,dt'$

k, m = constants $(0 \leq m < 2)$

Using the above equation and choosing suitable values for F(t) and m, all of the exponentially varying diffusion equations can be obtained as follows:

Fickian Solution: $F(t) = 1;\ m=0$

$$S(r,t) = \frac{M}{4\pi kt} \exp\left[-\frac{2}{4kt}\right] \qquad \text{(III-13a)}$$

k = diffusion constant, (cm^2/sec)

Joseph and Sendner Solution: $F(t) = 1;\ m = 1$

$$S(r,t) = \frac{M}{2\pi p^2 t^2} \exp\left[-\frac{r}{pt}\right] \qquad \text{(III-13b)}$$

p = "diffusion velocity", (cm/sec)

Ozimdov Solution: $F(t) = 1;\ m=4/3$

$$S(r,t) = \frac{M}{6\pi\,\gamma^3 t^3} \exp\left[-\frac{r^{2/3}}{\gamma t}\right] \qquad \text{(III-13c)}$$

γ = energy dissipation parameter $(cm^{2/3}/sec)$

Okubo and Pritchard Solution: $F(t) = t;\ m=0$

$$S(r,t) = \frac{M}{\pi\omega^2 t^2} \exp\left[-\frac{r^2}{\omega^2 t^2}\right] \qquad \text{(III-13d)}$$

ω = "diffusion velocity" (cm/sec)

Okubo Solution: $F(t) = t;\ m = 2/3$

$$S(r,t) = \frac{M}{\frac{3\pi}{4}^{3/2}\alpha^3 t^3} \exp\left[-\frac{r^{4/3}}{\alpha^2 t^2}\right] \qquad \text{(III-13e)}$$

α = energy dissipation parameter $(cm^{2/3}/sec)$

Obukhov Solution: $F(t) = t^2$, $m=0$

$$S(r,t) = \frac{M}{\pi\beta^3 t^3} \exp\left[-\frac{r^2}{\beta^3 t^3}\right] \qquad \text{(III-13f)}$$

β = energy dissipation parameter ($cm^{2/3}/sec$)

A comparison of these equations with theoretical predictions for peak concentration versus time, spatial distribution of diffusing material (value of the exponential decay) and variation of radius with time has been prepared by Okubo (58) and is tabulated in Table III-1.

Joseph and Sendner's equation will be used as a baseline for further discussion since it was the formulation described by Pritchard (60) in his report to the National Academy of Sciences - National Research Council. Dayton E. Carritt, Professor of Oceanography, Massachusetts Institute of Technology and Woods Hole Oceanographic Institute has prepared an evaluation of the diffusion and dilution of contaminants introduced into the sea. (61) Carritt used the same approach as Pritchard:

$$S(r,t) = \frac{nM}{2\pi D\,(pt)^2} \exp\left[-\frac{r}{pt}\right] \qquad \text{(III-14)}$$

where
- n = degree of restraint for diffusing material; n=1 for no restraint, n=2 for 180°, etc.
- M = amount of matter diffusing
- D = depth of initial mixing volume, cm.
- p = diffusion velocity, 1 cm/sec
- t = time, seconds
- r = distance from peak concentration, cm
- S = concentration of diffusing material

Using the WANL data* for fission product inventory for 3×10^{20} fissions and assuming complete solubility in the ocean waters for all elements but the noble gases, a graph similar to Carritt's

*See Table IV-9

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TABLE III - 1

SOME THEORETICAL PREDICTIONS DERIVED FROM THE PROPOSED SOLUTIONS FOR TWO DIMENSIONAL DIFFUSION [58]

Proposed Solution	Peak Concentration vs. Time	Spatial Distribution	Change of Radius Concentration	r_o of a Certain S_o with Time
	$\frac{S(o,t)}{M}$	$\ln \frac{S(r,t)}{S(o,t)}$	r_o	T_m
JS	$\frac{1}{2\pi p^2}\ t^{-2}$	$-\frac{1}{pt}\ r$	$pt \ln T/t$	T/e
Oz	$\frac{1}{6\pi\gamma^3}\ t^{-3}$	$-\frac{1}{\gamma t}\ r^{2/3}$	$(\gamma t \ln T/t)^{3/2}$	T/e
OP	$\frac{1}{\pi\omega^2}\ t^{-2}$	$-\frac{1}{\omega^2 t^2}\ r^2$	$(\omega^2 t^2 \ln T/t)^{1/2}$	$T/e^{1/2}$
Ok	$\frac{1}{3/4\ \pi^{3/2}\alpha^3}\ t^{-3}$	$-\frac{1}{\alpha^2 t^2}\ r^{4/3}$	$(\alpha^2 t^2 \ln T/t)^{3/4}$	$T/e^{1/2}$
Ob	$\frac{1}{\pi\beta^3}\ t^{-3}$	$-\frac{1}{\beta^3 t^3}\ r^2$	$(\beta^3 t^3 \ln T/t)^{1/2}$	$T/e^{1/3}$

Remarks:

- JS = Joseph and Sendner
- Oz = Ozmidov
- OP = Okubo and Pritchard
- Ok = Okubo
- Ob = Obukhov

T_m : time to reach maximum radius

T : duration of patch, i.e., the diffusion time when the radius being initially zero becomes zero again.

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is shown in Figure III-8. This figure depicts the decrease in concentration of soluble material with time for two initial conditions: two cylindrical volumes 10 m. and 100 m. in diameter each, and 10 m. in depth, of uniform concentration due to mechanical mixing prior to diffusion which follows a slope of t^{-2}. Superimposed on this diffusion is the radioactive decay up to 10^4 minutes (the limit of the WANL data). It should be noted that at 10^4 minutes after the excursion, decay contributes another reduction factor of 10^2 to the activity concentration in addition to that contributed by diffusion and dilution.

Further properties of the Joseph and Sendner equation are shown in Figures III-9 and III-10. Isopleths of concentration for the two initial conditions as a function of time and distance are displayed in Figure III-9. The 45 degree line has been drawn to show the time of maximum concentration at any distance from the center of the diffusing volume. It may be seen from this graph that the lines of constant concentration expand outward to a maximum radius and then return to the center. Figure III-10 is a plot of time isopleths as a function of mean concentration and distance. The two ordinates refer to the different initial conditions. Neither of these graphs incorporate radioactive decay, which accounts for an order of magnitude reduction in concentration beyond that derived from diffusion at one day, and two orders of magnitude at one week.

Variation of peak concentration with time is between t^{-2} and t^{-3} as observed in several studies reported by Okubo.[5,6] Carpenter[7] has reported on dye diffusion studies off Cape Canaveral with results which averaged around t^{-3} for one period of study. Concentration variations about the mean by a factor of two smaller and a factor of five larger might be observed on a particular occasion.

All of the discussion and the referenced equations above have only limited application to inshore waters due to the shearing action created by the shoreline and ocean bottom. These effects are expected to increase the rate of dilution but not necessarily isotropically. Direct application can only be made to the offshore waters of depths greater than 100 meters and distances of tens of kilometers.

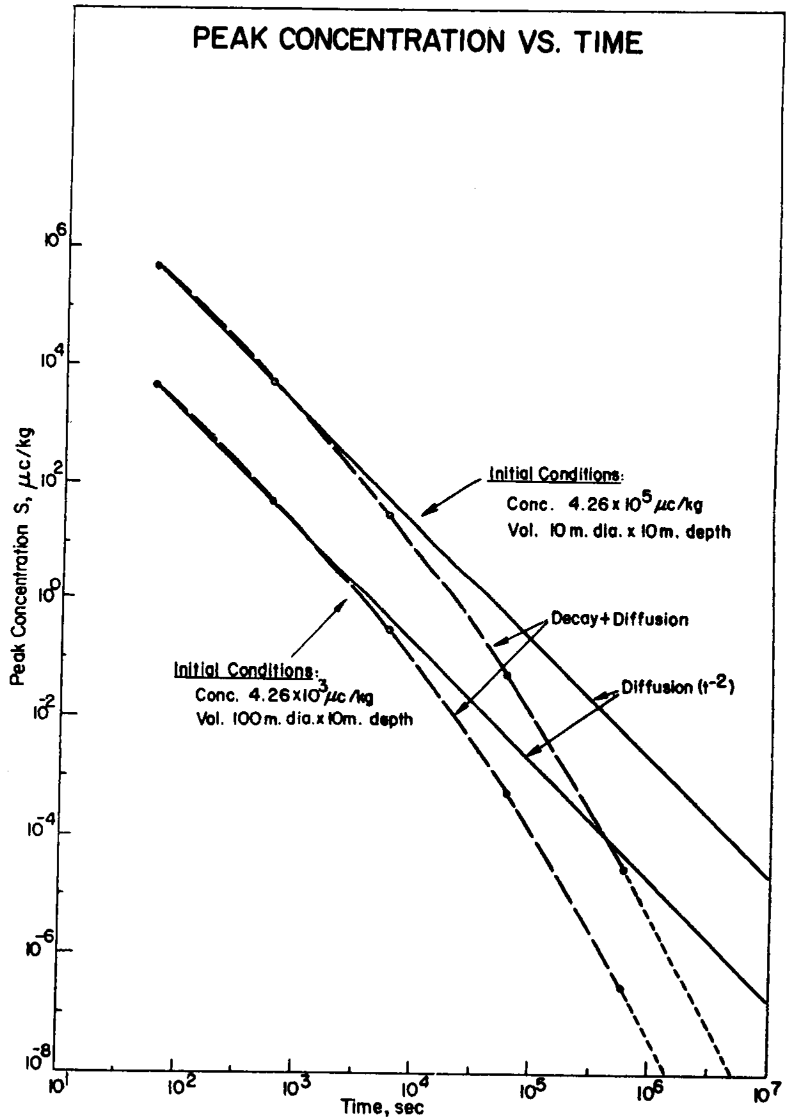

Figure III-8

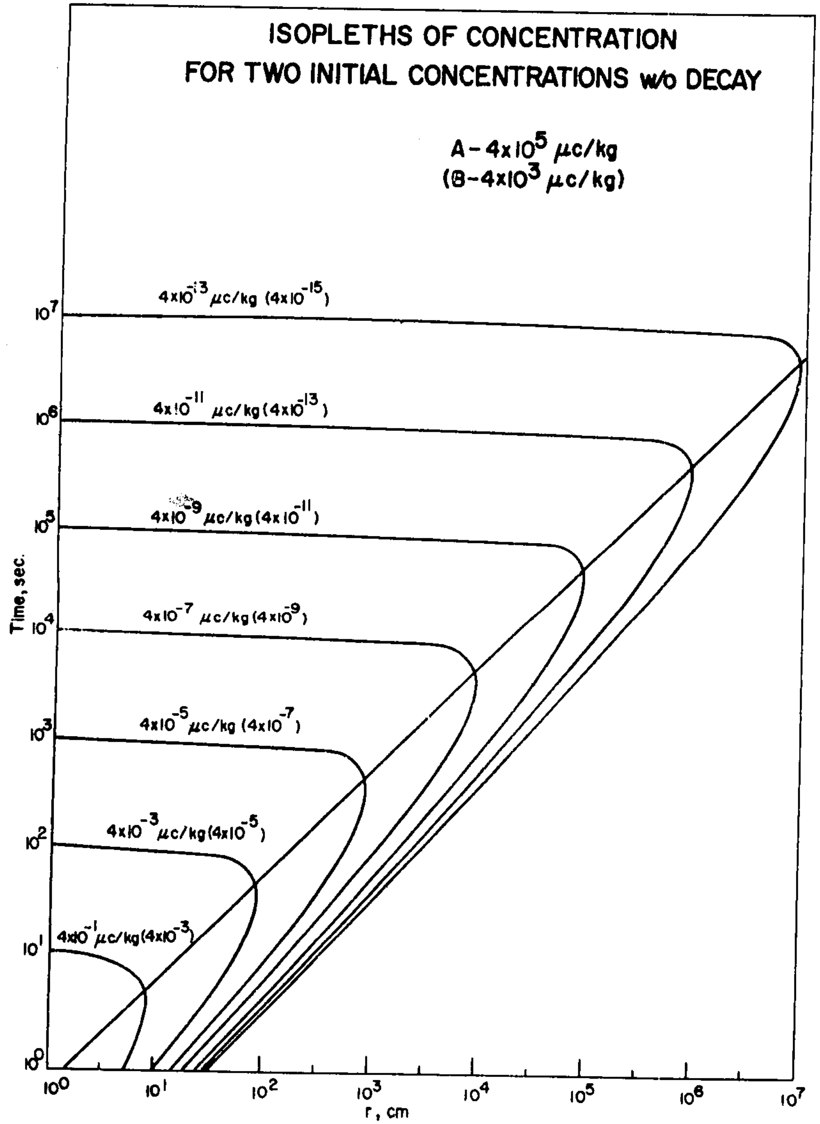

Figure III-9

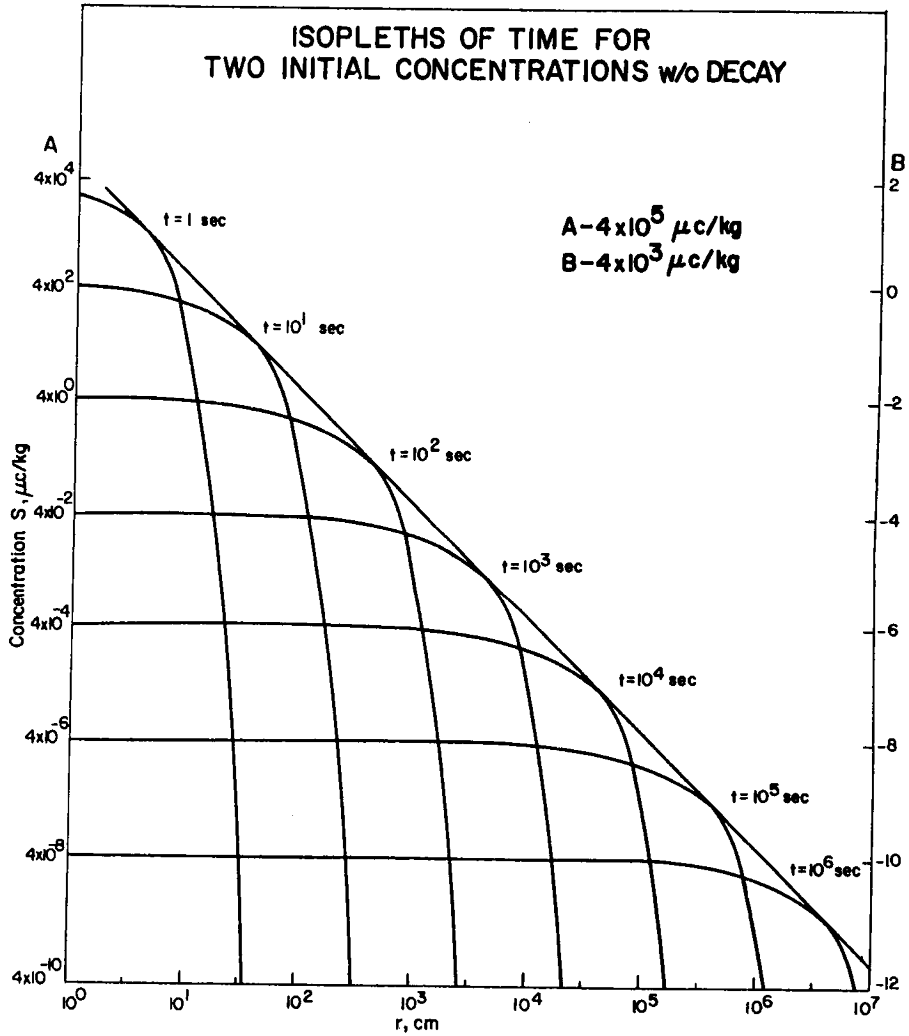

Figure III-10

In treating the Indian River Basin it is difficult to predict the movement of radionuclides in these shallow reaches. There is very little current except that derived from the winds. Tidal effects on the basin have not been measured but appear to be small. Short of conducting dye diffusion studies in these areas which are planned for the future, the only course left open to consideration at this time is the treatment of each section of the basin as a separate entity with insignificant interchange at the causeways, canals and inlets. A brief look at the characteristics of the Indian River Basin in Table III-2 will suffice to show the relatively small volumes of water at shallow depths that predominate in the lagoons and sloughs of the Basin. Additionally, dredging and filling operations which will accompany the development of the new launch complex and NASA industrial area will have a profound effect on the transport of material in the Indian and Banana Rivers.

In determining the hazard to man from the water immersion accident described in Section IV-E, the following models will be considered to apply:

a. Coastal waters - Joseph and Sendner's approach to diffusion and dispersion of soluble material will be applied;

b. Indian River Basin and Banana River - uniform distribution of the released fission products will be applied in each reach of the basins as defined above in Table III-2.

2. <u>Physico-Chemical Factors in Marine Transport</u> (57, 62)

In contrast to the effects of dilution and dispersion discussed above, sedimentation is a concentrating process consisting of the abstraction of dissolved and particulate material from sea water and its deposition on the sea bottom. When sedimentation of radioactive material occurs far from land in those areas relatively free of fish and marine organisms no problem is created. However, when sedimentation occurs in beach areas which man uses for recreation a potential direct radiation exposure to man may exist. Moreover, sedimentation in areas

TABLE III-2

INDIAN RIVER BASIN CHARACTERISTICS

	Area sq. meters	Avg. Depth meters	Volume liters
Mosquito Lagoon	1.16×10^{8}	1.0	1.16×10^{11}
Indian River			
N. of Titusville	9.26×10^{7}	1.75	1.62×10^{11}
Titusville to Cocoa	1.29×10^{8}	2.0	2.58×10^{11}
Cocoa to Eau Gallie	4.70×10^{7}	3.0	1.41×10^{11}
Eau Gallie to Melbourne	1.57×10^{7}	2.5	3.92×10^{10}
Banana River			
W. of Cape Canaveral	8.04×10^{7}	1.5	1.21×10^{11}
W. of Artesia	2.62×10^{7}	1.5	3.92×10^{10}
W. of Patrick AFB	7.80×10^{7}	1.5	1.17×10^{11}
		Total	9.93×10^{11}

where bottom feeding marine organisms exist may create potential human ingestion exposures.

Sedimentation is the last step in a series of physico-chemical actions of sorption, flocculation, ion exchange, precipitation and co-precipitation. In addition, the biological activity of marine organisms plays a major role which will be discussed below in Section III-C.

Figure III-11 shows a generalized scheme of the major physical, chemical and biological processes that occur in the sea. For the moment we will look a little more closely at the physical and chemical actions of flocculation, sorption, precipitation and ion exchange in the sea.

Flocculation or the formation of gelatinous precipitates, typical of alkaline aqueous media, is enhanced in the sea by normal pH range of 7.5 - 8.0. Solid particles and collodial matter are removed in this manner. Clay particles carried to the sea by runoff act as negatively charged nuclei which sweep out cations on contact producing a floc which will settle quickly under gravity.

Sorption is the process of accumulation of a gas, liquid or dissolved substance at internal and external interfaces. The process is dependent on the relationship between ionic charge, size and surface-to-volume ratio of the material to be sorbed and the sorbing surface. The nature of sorption is not yet clearly understood; however, it occurs on all suspended materials in the oceans. No quantitative estimates are available at this time.

Precipitation occurs when the product of the ionic concentrations exceeds the solubility product of a particular compound. Elements of Group II (Ca, Zn, Sr, Ba, etc.) form relatively insoluble sulphates and carbonates. By inference from the composition of the precipitated sediments in the sea the same elements calcium, iron, manganese and nickel in excess of normal amounts will precipitate out in the sea. The rare earths (Ce, Pr, Nd, Pm, etc.) precipitate rapidly due to solubility products in the range of 10^{-20} to 10^{-30}. Co-precipitation accounts for simultaneous precipitation of chemically similar elements. This occurs, for example, when calcium carbonate precipitation carries along strontium.

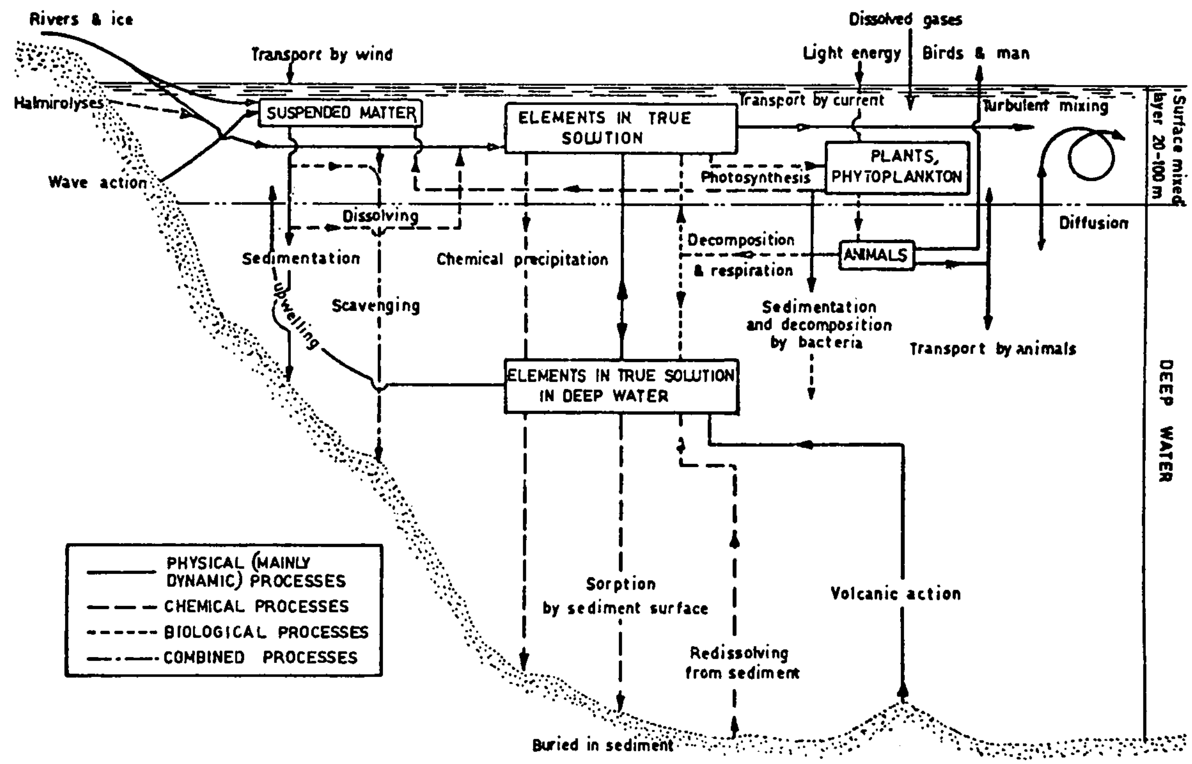

Figure III-11

PHYSICAL, CHEMICAL AND BIOLOGICAL PROCESSES IN THE SEA (69)

Ion exchange is another mechanism for concentration of ionic materials in the sea. Suspended clays and those on the sea bottom make up the major ion exchange constituent materials of the sea. Deep sea deposits have high base exchange properties (20 to 60 milliequivalents per 100 g of solid m.e.q.). Clay minerals' exchange capacities range from 60 to 100 m.e.q. for montmorillonite, to illite at 20 to 40 m.e.q., to a low of 3 to 15 for kaolinite. Probably ion exchange with the bottom surface deposits will be limited to the surface layers which will be saturated before significant penetration can occur.

As a result of all of these processes leading to sedimentation in the sea there is an accumulation of material on the ocean bottom. Rates of sedimentation for deep sea sediments such as red clay are on the order of a few millimeters per thousand years. Corresponding settling rates on the continental shelf areas are on the order of tens of centimeters, while in shallow areas sedimentation will be greater and highly variable depending on local conditions.

The particle washup problem has been considered briefly by Dean F. Bumpus, Oceanographer, Woods Hole Oceanographic Institute. (63) He believes that the washup of portions of the reactor will not be a problem unless the reactor impacts in the surf zone where under the action of waves, there will be washup. However, the material may not necessarily stay on the beach. In a study reported by Emery (64) on observations in Santa Monica Bay over a two year period tidal cusps were most abundant during small tides of summer and fall and at high tides. Tidal deposits were made up of fine gravel that culminated in a 8 cm. layer of medium to coarse gravel during a 4.5 hour rising tide. During the first 2.5 hours of falling tide, cusps were formed through erosion of the embayments by wave backwash which deposited some of the eroded material at the seaward side of the embayment to build the apex of the cusp. This change from bare sand to gravel cusp required only seven hours. Extrapolation of these observations to other gravel cusps in other regions is unknown.

For reactor impact outside the surf zones washup is unlikely because of the absence of long period swells and the absence of stones and pebbles on the Florida east shore. (63) Further investigations of the presence of gravel on the sea bottom and on the beach should be performed.

The nature of particles associated with a water immersion accident is ill defined at this time. However, dispersion of the core resulting from an excursion has been assumed to follow a particle size distribution as in Figure III-7 and described in the associated Section III-A.3. Surface dose rates described in that section will apply to this situation which will be discussed in Section IV-E.

3. Dose Delivery Models

Two primary modes of dose delivery to humans are prevalent in marine environments. The first results from immersion of individuals in a contaminated water volume, and the second from ingestion of contaminated sea foods. A third exposure source might result from the washup of core fragments on the beaches in the event of injection within 10 - 15 miles of shore. The sea food ingestion is treated in the following section, and the surface beta dose model employed for evaluation of particle washup is indicated in the previous discussion of airborne contaminants.

To determine the dose resulting from submersion in contaminated water the approach employed by NCRP (65) and ICRP (45) can be used. The individual is assumed to be at the center of an infinite hemispherical cloud of contaminated water; the resulting dose rate is 1/2 that in the center of an infinite cloud:

$$R_{sub} = \frac{C.\bar{E}.K}{\rho_w (\Phi_w/\Phi_t)} \text{ rads/hr} \qquad \text{(III-15)}$$

where: C = activity per cm^3, μc

E = effective energy per disintegration, Mev

ρ_w = density of water gm/cm^3 (= 1)

ϕ_w/ϕ_t = stopping power of water relative to tissue

K = conversion factor $(= 1.07 \frac{\text{gm-rad}}{\text{Mev-}\mu\text{c-hr}})$

If decay power, P, in the water is expressed in watts/cm^3, then

$$R_{sub} = \frac{P\,K'}{\rho_w(\phi_w/\phi_t)} \text{ rads/hr} \qquad \text{(III-15a)}$$

where: $K' = 1.8 \times 10^8 \frac{\text{gm-rad}}{\text{watt-hr}}$

C. BIOLOGICAL AND ECOLOGICAL RECONCENTRATION

1. Terrestrial Food Chains

Reconcentration of radioactive materials via the land-based food chain is a factor of great significance in the evaluation of hazard following a release of radionuclides. This is particularly true in the case of those foods where the freshness of the product is an important feature of its marketability, such as milk.

From the data on farm products presented in Section II-A.6, it can be seen that dairy cattle are not numerous in Brevard County. 308 were reported in the 1959 Census of Agriculture[17] and the value of dairy products sold was reported as $135,000. However, in Orange County immediately to the west, the value of dairy products sold in the same year was about $3,350,000, and the number of dairy cows, 6,668; in Volusia County, 3,117 milk cows produced about $640,000 in dairy products. Thus, radioactive material deposited at large distances from the launch area would affect an increasing number of dairy herds.

Evaluation of dose resulting from transmission of radioactive materials through the food chain is necessarily more tenuous due to the additional assumptions introduced by each link. In this study, milk is the only food item considered because of the promptness with which it transmits contamination to humans. It

must be recognized, however, that following an accident at Cape Canaveral which resulted in the release of large quantities of activity, surveillance of other food items for contamination would also be necessary.

In Section III-A.3, Equation (III-8) was presented from which acceptable "acute" (short-term) intake values were derived for Iodine-131, Strontium-89, Strontium-90 and Barium-140. From these values, acceptable initial intake values were derived which would not exceed FRC recommendations for internal dose. In order to relate the doses resulting from intake via milk to deposition on pastures, it is necessary to obtain an estimate of a "conversion ratio" for the cow.

Windscale experience [66] with Iodine-131 indicated that deposition of approximately one microcurie per square meter of grass yielded milk containing approximately 0.1 microcurie/liter. Using this ratio, the acceptable initial daily intake of 0.007 microcurie and an assumption of intake of one liter per day by a child, an initial limiting deposition for I-131 of about 0.07 $\mu c/m^2$ is derived.

The relationship between strontium on grass and in milk is less clearly defined. Strontium concentrations are usually indicated in terms of the ratio to stable calcium, since the biochemical behavior of the two elements is similar. Studies on the uptake of radiostrontium from food into the milk of cattle have been reported by Morgan, et al.[67] which indicated that the strontium/calcium ratio undergoes reduction by a factor of 10 from the diet (intake) to the milk of the cow. However, use of this relationship during the surveys following the Windscale incident indicated that the use of this relationship to predict strontium activity in milk gave results which were not confirmed by analysis. It was felt that this was due to errors in sampling the diet of the cattle, since the sampling of feces from the cattle to represent the dietary intake indicated a reduction in strontium/calcium ratio which approximated the anticipated factor of 10.

It is assumed that 2×10^{-4} microcurie of Strontium-90 is the permissible average daily intake value. Since the daily human intake of calcium is approximately one gram, the strontium/calcium ratio in the human diet from milk would be approximately 2×10^{-4} microcuries per gram of calcium. With a ten to one, diet to milk, reduction in this ratio through the cow, the resulting cow diet concentration would be 2×10^{-3} microcuries Sr-90 per gram of calcium. Assuming an average daily intake of 100 grams of calcium for the cow, this results in a daily total intake by the cow of 0.2 microcuries of Strontium-90. Assuming an intake of approximately ten kilograms of grass per day (from ten square meters) this would imply deposition of 0.02 microcuries of Sr-90 per square meter of pasture.

It should be recognized that a number of assumptions implicit in this derivation are tenuous and based on extremely meager data. The ten square meter per day grazing figure derives from a measured intake of grass for English cattle (67) of approximately 11 kilograms per day and measured mass concentration of grass approximating one kilogram per square meter. This value would have to be correlated to the pasture characteristics and grazing habits of cattle in the vicinity of Cape Canaveral.

A similar exercise for Strontium-89 would yield permissible pasture surface contamination of 6.6 microcuries per square meter and assuming the same uptake and distribution characteristics for Barium-140 as for strontium, a value of 490 microcuries per square meter.

From the data indicated in Section II-A.6, it is apparent that other crops must be considered in an evaluation of the terrestrial food chain transmission route to man. This analysis is concerned only with the transmission of radioactive materials via milk, which appears on the basis of fallout studies and experience at Windscale to offer the most significant route. However, in view of the large agricultural industry within 50 miles of Cape Canaveral, predominantly in citrus culture, it seems essential to recognize that other crops may well be significantly affected by the deposition of radioactive material from airborne clouds.

No consideration has been given in this study to the effect of root irrigation of crops with contaminated water, since it appears that such contamination would be detected sufficiently in advance of

the sale or use of such crops to prevent distribution of those contaminated with harmful amounts of radioactivity. In any event, the occurrence of a major accident involving a nuclear stage at Cape Canaveral should require the careful and intelligent evaluation of environmental contamination and subsequent monitoring of affected crops should be carried out in those areas indicated by preliminary measures to be affected.

2. Marine Food Chain

Biological reconcentration of radionuclides by plants and animals in the marine food chain with subsequent ingestion by man is a potential source of internal exposure to man. A description of the various forms of marine life significant to the movement of radionuclides through the marine environment is shown in Figure III-12.[57]

Marine bacteria decompose the particulate organic matter and take up dissolved elements in the sea. Large fluctuations of marine populations exist with concomitant rapid changes in the levels of soluble elements. On the death of the bacteria the elements are released to the environment for subsequent uptake by other organisms including bacteria. Abundance of marine bacteria is higher in coastal and surface waters than in off-shore waters at great depths.

Phytoplankton and seaweeds produce organic matter by photosynthesis using nutrient salts from the sea water. While phytoplankton is not used directly for human food it is consumed by zooplankton, by some filter-feeding fish and by some bottom-dwelling animals. Phytoplankton is found in surface layers due to dependence on solar energy for photosynthesis while seaweeds are found attached at depths as great as 300 feet. The larger seaweeds such as kelp are used for human food or crop fertilizer in some areas and were found to be the controlling factor in the diet of populations in the environment of Windscale due to its concentration of ruthenium.[68] They are not used in the Cape Canaveral area.

Zooplankton feeds on phytoplankton and other zooplankters with these as his main source of intake of radionuclides along with the corresponding stable form of the elements. Zooplankters are the main

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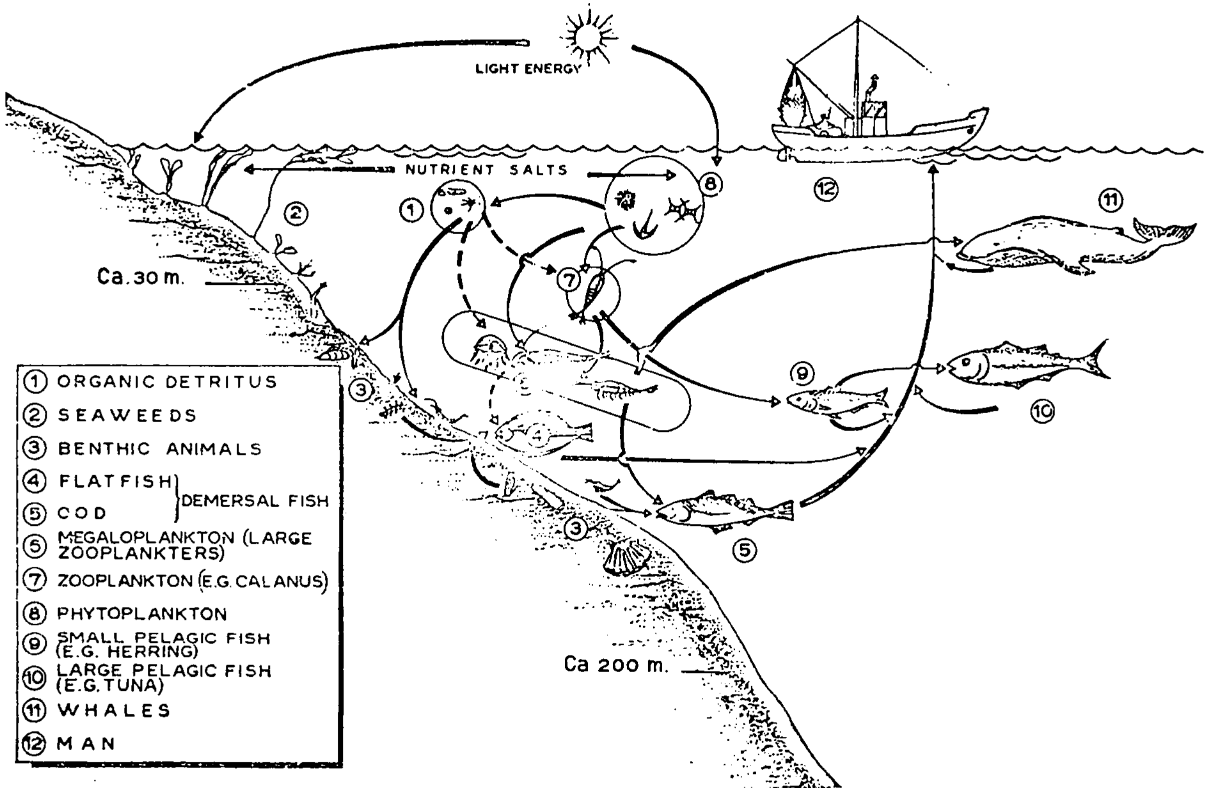

Figure III-12

MARINE FOOD CHAINS (62)

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supply of food of some pelagic (free-swimming) fish. Some zooplankters are eaten by humans directly, such as squid. Benthic animals such as oysters, lobsters, shrimp, etc. spend most of their life on the bottom of the sea. Uptake of radionuclides by these organisms occurs by filtering of sea water and mud suspensions, feeding on detritus or eating of other benthic organisms, direct absorption from sea water, and by contact with the bottom.

Demersal (bottom-dwelling) fish, flatfish and cod, spend most of their life on the bottom and feed partly on benthic animals. They do make diurnal vertical migrations to obtain the remainder of their diet. Seasonal and specie characteristics cause large variations to occur in the population of any given area of the sea bottom.

Pelagic fish vary in their feeding habits from filter feeders on plankton to the larger varieties, e.g., tuna and bluefish, which feed on the small pelagic fish such as herring and menhaden.

Sea birds may pick up contaminated organisms while feeding in the inter-tidal zone and transport the material over large distances inland. This does not appear to present a problem at this time.

As mentioned previously in Section II-A.6, there are very active and lucrative commercial fisheries in the vicinity of Cape Canaveral amounting to about $1.6 million in 1960.[20] Shrimp is the most valuable fishery in the area, and is located in a narrow belt adjacent to the coast. Exploratory fishing operations have indicated that commercial concentrations of the royal sea shrimp exist just off the Blake Plateau and in the Gulf Stream waters at 900 to 1500 ft. depths. In addition, a potentially valuable scallop bed exists in 60 - 180 ft. waters over a 1200 square mile area from Daytona Beach to Ft. Pierce.

Sport fisheries are a very significant activity in the Cape Canaveral area, both offshore and in the relatively shallow Banana and Indian River Basins. Additionally, migratory waterfowl which inhabit these basins in large numbers during the winter season are a potential source of transport of contaminated material that may be present.

With the above information on marine food chain and the existing and potential fisheries kept in mind, it is appropriate at this time to consider the effect of an introduction of radionuclides into the marine environment and a determination of suitable guidelines for evaluation of dose to the human population that eats marine foods. The Working Group of the Committee of Oceanography of the National Academy of Sciences -- National Research Council, under the Chairmanship of John D. Isaacs, has recently prepared a document on the disposal of radioactive waste into Pacific Coastal waters.(69) Guidelines setforth in this document are based on a specific activity approach which requires a knowledge of the stable element composition of the marine food ingested and its environment along with a similar knowledge of the human body and its various organs. Two situations were described in the report which govern the assessment of the hazard of a particular radionuclide which includes the type and energy of the radiation, the radio-sensitivity of the organs involved, the physical half-life of the nuclide and its daughter products:

a. "where the hazard results from absorption of an isotope by the body, it is apparent that if this allowable specific activity for an element in the human body is not exceeded, the allowable body burden will not be exceeded;

b. "where the hazard results not from absorption into the body but from the irradiation of the gastrointestinal tract by its contents, it is apparent that a related specific activity for the elemental composition of sea food is not exceeded, the allowable MPC will for these elements not be exceeded."

The problem of determining maximum permissible concentrations in sea water can be then stated simply as follows:

"if the specific activities of the elements of the sea in one region of growth, development and habitation of marine food organisms can be maintained below the allowable specific activities of these elements in man and his seafood, the allowable radiation for any individual cannot be exceeded as a result of the consumption of marine products."

Applying this approach to the point in question and utilizing the ICRP (45) data for maximum permissible body burden in man, a maximum permissible specific activity of the stable species of the element in the critical organ was derived by applying a factor for the abundance of the element in that organ. This value was then modified by the ratio of the sum of the physical and biological decay constants to the biological decay constant in man. In the case where irradiation of the GI tract is the controlling exposure, the drinking water MPC (45,65) was converted to a maximum permissible specific activity of the stable species of the element in seafood, utilizing the abundance of that element in the seafood organisms that result in the most restrictive requirement. Subsequently, these values were reduced by a factor of ten for the general population and in some cases by a factor of one hundred when it was believed the elements introduced in the sea would be present in an organic complex which would not be diluted in the same manner as the common and more abundant form of the stable element. These organically complexed elements are the lighter elements and are not of concern in the case discussed here. Fission products conventionally thought of as internal hazards to man from ingestion are Sr-89 and -90, Cs-137, I-131, Ba-La-140, Ce-Pr-141 and -144. However these are not necessarily a potential problem in the marine ecological food chain to man due to the presence in the sea of stable forms of these radionuclides. Table III-3 is a list of the concentrations of elements in sea water.(62) Little information is available on the abundance of the rare earths and the transition elements in the sea. The presence of a significant amount of stable strontium reduces the potential hazard of its radioactive species, particularly when this is combined with the fact that Strontium-90 is not concentrated in the soft tissues of the marine organisms over its concentration in the sea water. The calcified portion of marine organisms does concentrate strontium but this is not a normally edible portion of seafood.(70) Where the entire animal is marketed such as herring, sardines, and fish meal, this may be a problem. Table III-4 is a tabulation of the concentration factors of various elements by marine organisms.(69,70,71) Cesium is accumulated to relatively high levels by soft tissues of marine fish and invertebrates. In general, concentration factors of 20 - 50 times that of the surrounding sea water

TABLE III-3

CONCENTRATION OF ELEMENTS IN SEA WATER (62)

		Group	mg/l
	H	I	108,000
	He	VIII	0.000005
	Li	I	0.2
	Be	II	
	B	III	4.8
	C	IV	28
	N	V	0.5
	O	VI	857,000
	F	VII	1.3
	Ne	VIII	0.0003
	Na	I	10,500
	Mg	II	1,300
	Al	III	0.01
	Si	IV	3
	P	V	0.07
	S	VI	00
	Cl	VII	19,000
	A	VIII	0.6
	K	I	380
	Ca	II	400
Transition Elements	Sc	III	0.00004
Transition Elements	Ti	IV	0.001
Transition Elements	V	V	0.002
Transition Elements	Cr	VI	0.00005
Transition Elements	Mn	VII	0.002
Transition Elements	Fe	VIII	0.01
Transition Elements	Co	VIII	0.0005
Transition Elements	Ni	VIII	0.0005
Transition Elements	Cu	I	0.003
Transition Elements	Zn	II	0.01
	Ga	III	0.0005
	Ge	IV	< 0.0001
	As	V	0.003
	Se	VI	0.004
	Br	VII	65
	Kr	VIII	0.0003
	Rb	I	0.12
	Sr	II	8
Transition Elements	Y	III	0.0003
Transition Elements	Zr	IV	
Transition Elements	Nb	V	
Transition Elements	Mo	VI	0.01
Transition Elements	Tc	VII	
Transition Elements	Ru	VIII	
Transition Elements	Rh	VIII	
Transition Elements	Pd	VIII	
Transition Elements	Ag	I	0.0003
Transition Elements	Cd	II	0.000055
	In	III	< 0.02
	Sn	IV	0.003
	Sb	V	< 0.0005
	Te	VI	
	I	VII	0.05
	Xe	VIII	0.0001
	Cs	I	0.0005
	Ba	II	0.0062
Lanthanide Series	La	III (Rare Earth)	0.0003
Lanthanide Series	Ce	"	0.0004
Lanthanide Series	Pr	"	
Lanthanide Series	Nd	"	
Lanthanide Series	Pm	"	
Lanthanide Series	Sm	"	
Lanthanide Series	Eu	"	
Lanthanide Series	Gd	"	
Lanthanide Series	Tb	"	
Lanthanide Series	Dy	"	
Lanthanide Series	Ho	"	
Lanthanide Series	Er	"	
Lanthanide Series	Tm	"	
Lanthanide Series	Yb	"	
Lanthanide Series	Lu	"	
Transition Elements	Hf	IV	
Transition Elements	Ta	V	
Transition Elements	W	VI	0.0001
Transition Elements	Re	VII	
Transition Elements	Os	VIII	
Transition Elements	Ir	VIII	
Transition Elements	Pt	VIII	
Transition Elements	Au	I	0.000004
Transition Elements	Hg	II	0.00003
Transition Elements	Tl	III	< 0.00001
	Pb	IV	0.003
	Bi	V	0.0002
	Po	VI	
	At	VII	
	Rn	VIII	9.0×10^{-15}
	Fr	I	
	Ra	II	3.0×10^{-11}
Actinide Series	Ac	III	
Actinide Series	Th	IV	0.0007
Actinide Series	Pa	V	0.003
Actinide Series	U	VI	
Actinide Series	Np	VII	
Actinide Series	Pu	VIII	
Actinide Series	Am	VIII	
Actinide Series	Cm	VIII	
Actinide Series	Bk		
Actinide Series	Cf		

TABLE III-4

MARINE ORGANISM CONCENTRATION FACTORS

		Isaacs (69)	Goldberg * (71)	Krumholz ** (70)
Rb	Rubidium	2×10^2		
Sr	Strontium	2×10^1		
Y	Yttrium	1×10^3		
Zr	Zirconium	1×10^3		
Nb	Niobium	2×10^2		
Tc	Technetium	5×10^4		
Ru	Ruthenium	5×10^4		
Cd	Cadmium	2×10^4	$>4.5 \times 10^3$	
In	Indium	4×10^5		
Sn	Tin	2×10^3	2.7×10^3	
Sb	Antimony	1×10^2	$>3 \times 10^2$	
Te	Tellurium	1×10^2		
I	Iodine	1×10^4		
Cs	Cesium	5×10^1		10^1
Ba	Barium	5×10^2		
La	Lanthanum	1×10^3		
Ce	Cerium	1×10^3		
Pm	Promethium	1×10^3		
Sm	Samarium	1×10^3		
Eu	Europium	1×10^3		
Ta	Tantalum	1×10^3		
As	Arsenic		3.3×10^3	
Bi	Bismuth		1×10^3	
Ga	Gallium		8×10^2	
Ge	Germanium		$>7.6 \times 10^3$	
Mo	Molybdenum		6×10^3	10^2
Ag	Silver		2.2×10^4	

*Total organism, nine species of marine organisms from Swedish fjord analyzed by optical spectroscopy reported on dry basis.
**Soft tissue, invertebrates on live-weight basis.

have been found, depending on the organism and tissue concerned.[20]

Much of the experimental work on uptake of radionuclides in marine organisms has been done without due regard to the significance of the presence of stable elements in the environment and in the organisms themselves. In the absence of better data which will include considerations of pH, temperature and specific activity as parameters, the values used in the Isaacs report will suffice. Further, the values for maximum permissible concentration in sea water listed in the Isaacs report will be used as guidelines for the appropriate evaluation of marine food ingested by man.

Figure III-13 [62] is a summary of the various factors contributing to the movement of radionuclides through the physical, chemical and biological environment of man. The diluting and dispersing processes which are primarily dynamic and physical are placed side-by-side with the concentrating mechanisms which are biological and chemical. These manifold processes prove the difficulty in intelligently evaluating the problem of reconcentration and transport of contaminants via the sea to man.

CONFIDENTIAL

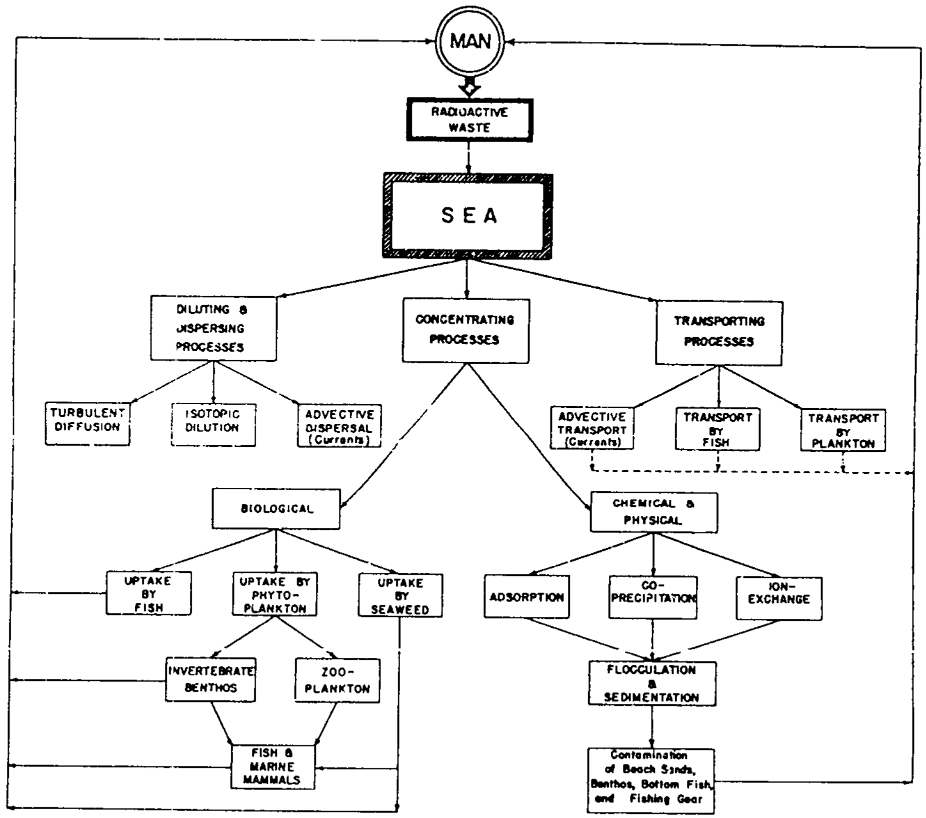

Figure III-13

MOVEMENT OF RADIONUCLIDES THROUGH THE ENVIRONMENT TO MAN [62]

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IV. LAUNCH SITE HAZARD EVALUATION

A. REFERENCE DESIGNS

In order to provide a basis for system analysis, several assumptions must be made with respect to the chemical vehicle, the nuclear stage and NERVA reactor, recognizing that final designs for these systems have not as yet been specified. These so-called reference designs are intended to provide a frame-of-reference for the present hazards analysis, and to provide a basis for indicating, as changes in the system are introduced, the significance (in terms of hazards) of these modifications.

The features of obvious importance to this analysis are concerned with the nuclear reactor - its material and structural arrangement and its dynamic behavior, in a nuclear, physical, and chemical sense. Features of the remainder of the assembled vehicle are important insofar as they create potential forces of various kinds which may act upon the NERVA reactor.

1. Nuclear Stage (SN)

a. Reactor

Table IV-1 presents the operational specifications of the NERVA engine. The mechanical design specified as the reference for this study is that of the KIWI B-4, which has been described in detail elsewhere.(72-76) Figures IV-1 and IV-2 depict an assembly cutaway and an axial section of the Los Alamos KIWI B-4A.(77)

The reference fuel system consists of uranium dicarbide particles (100-150 micron diameter) coated with a 25 micron layer of pyrolytic carbon and dispersed uniformly in a graphite matrix. Hexagonal fuel elements are 19 mm across the flats, pierced with 19 coolant channels 0.094 inches in diameter. Fuel assemblies shown in Figure IV-3 are composed of clusters of six fueled elements surrounding a central unfueled graphite element which houses a stainless steel support rod insulated by a pyrolytic graphite sleeve.

TABLE IV-1

OPERATIONAL SPECIFICATIONS OF THE NERVA REACTOR

Reactor Power	1120 MW(t)
Engine Thrust, nominal	56,100 lb.
Operating Period	30 minutes
Reactor Coolant	Hydrogen
Flow	71.3 lb/sec
Inlet Temperature, mean	-150° C
Exit Temperature, mean	2000° C
Exit Pressure, mean	550 psia

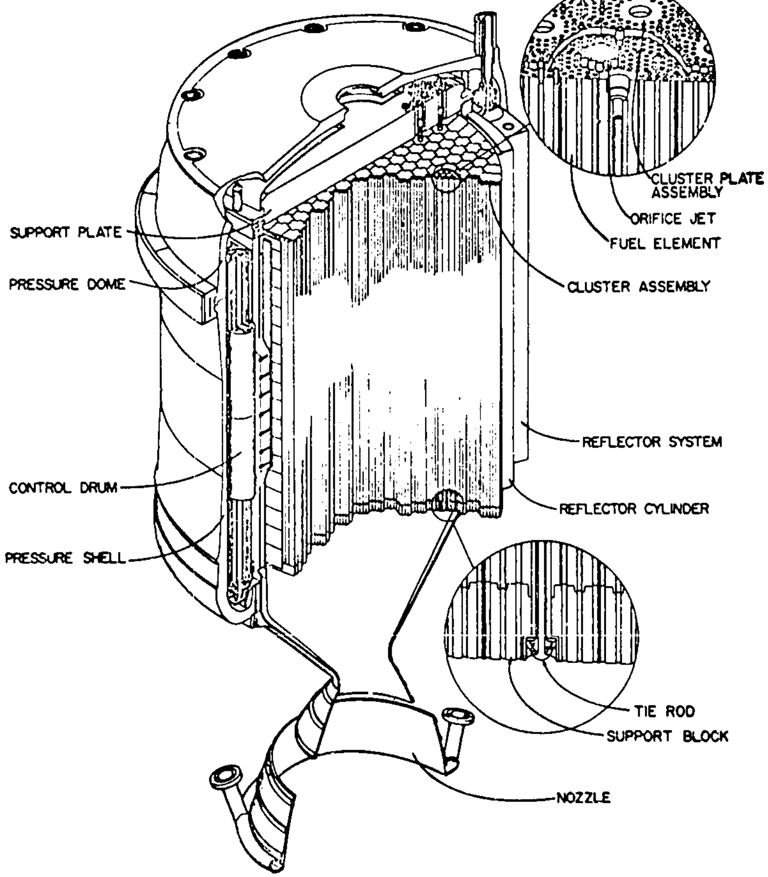

Figure IV-1

KIWI B-4A REACTOR ASSEMBLY CUTAWAY (77)

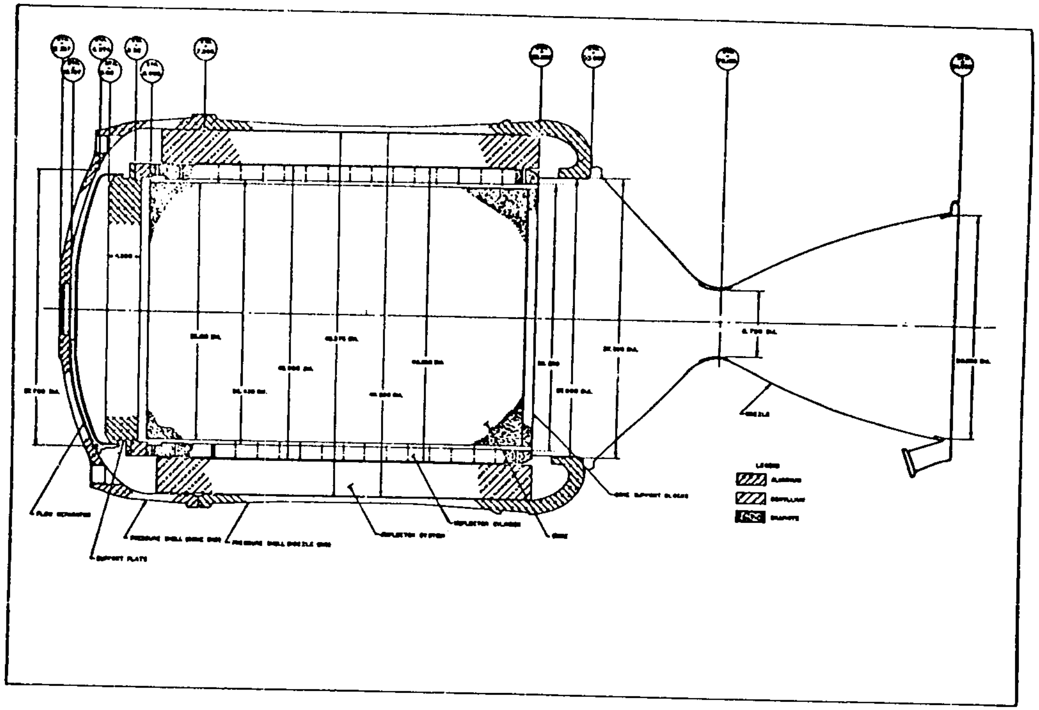

Figure IV-2

KIWI-B-4A AXIAL SECTION [77]

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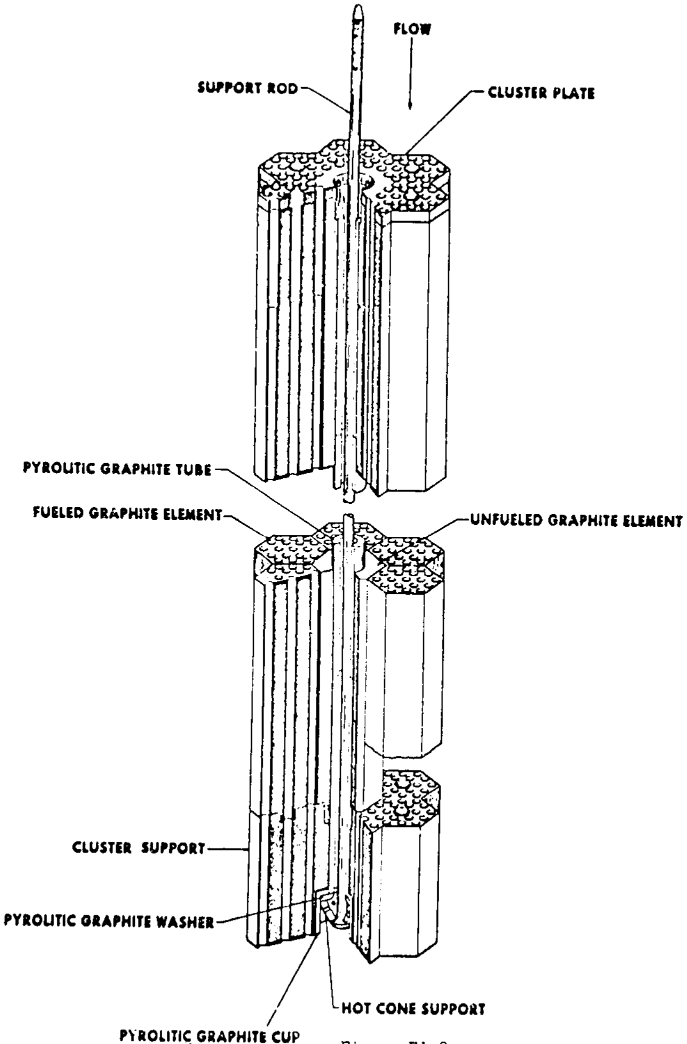

Figure IV-3

KIWI B-4 Fuel Cluster (74)

Pertinent dimensions of the reactor system are tabulated below:(73)

	Inner Radius	Outer Radius	Height
Core	--	45.0 cm	128 cm
Graphite Sleeve	45.0 cm	46.47	128
Void	46.47	46.84	128
Graphite Reflector	46.84	50.64	128
Void	50.64	50.96	128
Beryllium Reflector	50.96	62.39	128
Void	62.39	62.55	128
Pressure Vessel	62.55	63.98	128
Support Plate	0	45.0	15.2

The KIWI B-4 core constituents, by volume fraction, are tabulated below:

Constituent	Volume Fraction
Fueled graphite	0.584
Unfueled graphite	0.119
Pyrographite	0.0166
Void	0.264
Niobium coating	0.0119
Stainless Steel (tie rods)	0.0041

The core heat capacity for the reference design is computed(73) to be 3.1 joules/gm-^{o}C. System component weights are for the core assembly 1,800 Kg (including 189 Kg Uranium-235 and about 1,000 Kg of carbon in the core); and for the beryllium reflector, 1,000 Kg. The reactor core and reflector assembly are housed in a titanium pressure vessel.

Considerable amounts of data have been accumulated for previous KIWI designs, B-1 and B-2. A comparison with B-4 is useful. The prompt neutron lifetimes for the B-1 and B-4 systems are 11.5×10^{-6} sec and $\sim 25 \times 10^{-6}$ sec, respectively. While the total fission energy yield from prompt excursions is relatively independent of the neutron lifetime, the width of the spike and the maximum power are prompt lifetime dependent.[78] Hence, peak powers are larger for the B-4 reactor. In addition, there are significant reactivity differences between the B-1, B-2 and B-4 systems, as Table IV-2 discloses.[73] Specifically, it is noted that a net increase in reactivity from cold to hot is expected in the B-4 core while a net decrease is known to occur for the B-1 and B-2 cores due to temperature and volume fraction differences of the hydrogen in the respective designs. The result is that, on the basis of the model used, the B-4 system develops increased energy from a prompt burst before compensation mechanisms such as core expansion, vaporization, etc., occur. The B-4 yields are treated further in IV-B below, and a discussion of the computation scheme from which these yields are obtained is presented in Appendix A.

It should be noted that the selection of the KIWI B-4 mechanical design as reference is arbitrary. It is unlikely that the exact configuration and mode of core support will remain unchanged through the extensive test program envisioned prior to the first RIFT launch.

b. Non-Nuclear Components

The reactor provides the heat source for expansion of the propellant out the nozzle; the remainder of the nuclear stage provides the storage and feed system for some 147,000 pounds (maximum) of liquid hydrogen propellant, as well as the guidance and command systems, etc.

2. Chemical Booster

A three-stage vehicle is assumed: the SN (nuclear) third stage previously described; a second chemical stage consisting of a high impulse LOX-LH_2 rocket of the Centaur type; and a chemical booster first stage of the configuration of the Saturn C-5 system. Table IV-3 presents the propellant inventories of these two chemical stages. Figure IV-4 depicts the geometrical relationships with stage dimensions. While the suborbital, ballistic trajectory two-stage system (utilizing water ballast to simulate the second chemical stage mass) is to be used for the RIFT program, the reference configuration

TABLE IV-2

SUMMARY OF CALCULATED REACTIVITY WORTHS

	B-1 and B-2	Uniformly Loaded B-4 Type
Reactivity Worth of Hydrogen in Core, $(\Delta k/k)/kg$	0.071	0.060
Reactivity Worth of Hydrogen in Reflector, $(\Delta k/k)/kg$	0.002	0.0018
Temperature Coefficient of Reactivity at Operating Conditions, $(\Delta k/k)/^{\circ}R$	-0.96×10^{-5}	-1.0×10^{-5}
*Loss in Reactivity from Cold (no hydrogen) to Hot Operating Condition (with hydrogen), $\Delta k/k$	0.0077	-0.026
Reactivity Worth of All Drums, Full in to Full out, $\Delta k/k$	0.089	0.10
Reactivity Worth of Peak Xenon After Shutdown, $\Delta k/k$	0.0016	--

* Note that there is a net increase in reactivity in going from the cold to hot condition for the B-4 while a net decrease for the B-1 and B-2. This results primarily from temperature and volume fraction differences of the hydrogen in the respective cores.

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TABLE IV-3

STAGE PROPELLANT INVENTORIES

S I C C-5 Booster

LOX	3.1×10^6 #		
RP-1	1.375×10^6 #		
		Total -	4,475,000 #

S II C (Centaur Type)

LOX	592,000 #		
LH_2	148,000 #		
		Total -	740,000 #

SN (LH_2)

LH_2	147,200 #		
		Total -	147,200 #

Equivalent H.E.

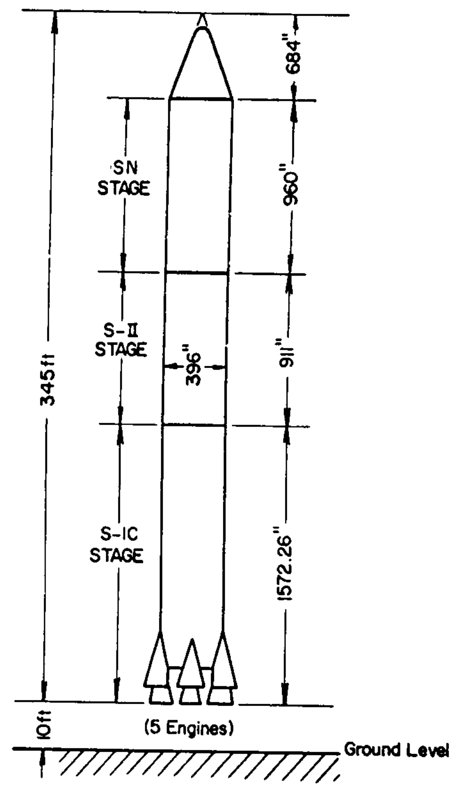
RP-1 + LOX:

4,475,400 # x .10 = 447.540 #

LH_2 + LOX:

(740,000 + 147,200) x .60 = 532,320 #

Total Equivalent H.E. - 979,860 #



SATURN C-5 VEHICLE

Figure IV-4

chosen for this study is that of the orbital three-stage vehicle for purposes of having available the largest flammable fuel inventory foreseeable for certain of the accident cases to be considered (see Section IV-B-2) with NERVA launches.

B. DESCRIPTION OF THE ACCIDENTS CONSIDERED

To postulate all of the potential forms of failure and energy release for the Saturn-NERVA system would require an infinite number of cases. Were the technical base developed at this time to permit rigorous analysis of any single causal event, the resulting task would be a most formidable assignment. The fact of the matter is that much of the technical information required is not now available, which forecloses the possibility of developing in a precise, quantitative manner the energy yield and resulting radiological source terms from a large reactivity insertion due to some untoward causal event. Present uncertainties are discussed in Section VII and Appendix A.

One need only consider a portion of the presently unresolved questions to realize that an exact solution will never be found. What can be done fruitfully, however, is to ascertain the upper boundary of a number of energy releases based on reasonably credible, though improbable, causal events, estimate the fission product release in a conservative manner, and present the resulting doses as a function of distance with appropriate uncertainty factors. Consistent with past approaches to conventional nuclear reactor hazard evaluation, no quantitative estimates of accident probability are used.

This approach forms the basis for the NUS hazard analysis of nuclear rocket flight operations from Cape Canaveral. Specifically, five cases are described below in considerable detail, based on the LASL computational model described in Appendix A. Additionally, one case cited by LASL for which an estimate has not been offered (core implosion from a Saturn propellant fuel detonation) is treated based on an NUS interpretation of LASL computations. From these six cases described in the following section, three generalized hypothetical occurrences are assumed whose effects are analyzed in detail in subsequent sections.

1. Specific Accident Descriptions

The possible NERVA accidents appear to range from conceivably violent explosions with substantial core vaporization or disassembly

(liquid H_2 or H_2O injection from pump malfunction or water impact, respectively), to relatively mild power and temperature excursions (partial reflection or single control vane "runout" malfunction). Five accidents have been considered which essentially fill this continuum of energy release:

(1) Core implosion within the liquid detonating region of a Saturn C-5 booster fire explosion.
(2) Water accidents
  (a) High velocity water injection in core from water impact.
  (b) Complete water reflection from core immersion (no water in core).
(3) Core deformation from land impact.
(4) Liquid hydrogen injection in core through pump malfunction.
(5) Gross control vane "runout" malfunction.

In addition, an estimate of the effect of the coated fuel particles is offered. (These and coolant channel heterogenieties are not incorporated in the machine analyses.)

a. Core Implosion

The probability of immersion of the reactor in a detonating liquid propellant mixture appears exceedingly small. Nonetheless, the extreme peak pressures developed in the liquid detonating region of a LOX-LH_2-RP-1 propellant explosion warrant consideration of the extent of core compression which might result from this accident. A study of the explosive hazard associated with the Saturn vehicle and its effect on a nuclear rocket engine has been conducted by Arthur D. Little, Inc.[80] The spilling and mixing of the approximately 5,000,000 pounds of C-5 liquid propellant would create a two-phase mixture: a gas phase consisting of hydrogen, oxygen, and air; and a liquid phase containing RP-1, oxygen, and some hydrogen. Ignition of the mixtures would yield a violent detonation with peak pressures in the liquid phase of 7,000 to over 90,000 psi, and in the gas phase of the order of 100 to 2,000 psi. The maximum pressure developed in the liquid phase is dependent upon mixture homogeniety, the highest pressures occurring in regions with the greatest degree of mixing. Theoretical pressures attainable in liquid hydrogen-oxygen mixtures are computed to approach 150,000 psi.[81,82] Peak pressures decrease rapidly with distance from the liquid phase.

It is unrealistic to assume that the total C-5 propellant inventory would contribute to the detonation reaction. Asymmetry in the mode of failure of the vehicle alone would effect a reduction in the concentration and mixing of the propellant stored. Figure IV-5 which depicts the dimensions of the zones of the detonation region is based on:

(1) the results of an extensive scaled experimental program by A. D. Little, Inc.,[83] wherein liquid detonation zone dimensions and gaseous vapor dimensions were taken from crater measurements and photographic records, respectively, and scaled to a C-2 inventory.

(2) a fraction of the total fuel inventory of the RIFT system available for detonation, as proposed by the Range Safety Division, Patrick AFB for other liquid and solid propellant missile systems.[79]

The Range Safety study has proposed a TNT pound equivalency of 10 percent of the total weight of the combined LOX-RP-1 booster fuel inventories (4,475,000 pounds in SIC of Saturn C-5), and 60 percent of the Centaur type LOX-LH_2 fuel inventories (740,000 pounds in SIIC for orbital missions, plus a maximum of 147,200 pounds of LH_2 for the SN stage). The Arthur D. Little, Inc., study has in turn established the equivalency of pounds of TNT per pound of propellant[83] as shown in Table IV-3. This study has, therefore, assumed equivalency between TNT and propellant on a pound-for-pound basis, thus reducing the total fuel inventory to a realizable detonation equivalent on the basis proposed by the Range Safety Division, Patrick AFB. The total explosive equivalent inventory on this basis is 978,860 pounds, or approximately 1,000,000 pounds.

The spatial distribution of peak pressures at ground level based on a symmetrical idealized reaction (detonation) of this reduced fuel inventory is that shown in Figure IV-5. The Saturn C-5 realizable detonation equivalent of approximately 1,000,000 pounds coincides with the Arthur D. Little, Inc., treatment of a detonation of a Saturn C-2 with a <u>total</u> fuel inventory of approximately 1,000,000 pounds. Thus, the ADL predicted pressure conditions for a full scale C-2 failure apply to the present treatment of a C-5 failure and are summarized in Table IV-4.

SATURN C-5 DETONATION PRESSURES

VS. RADIAL DISTANCE

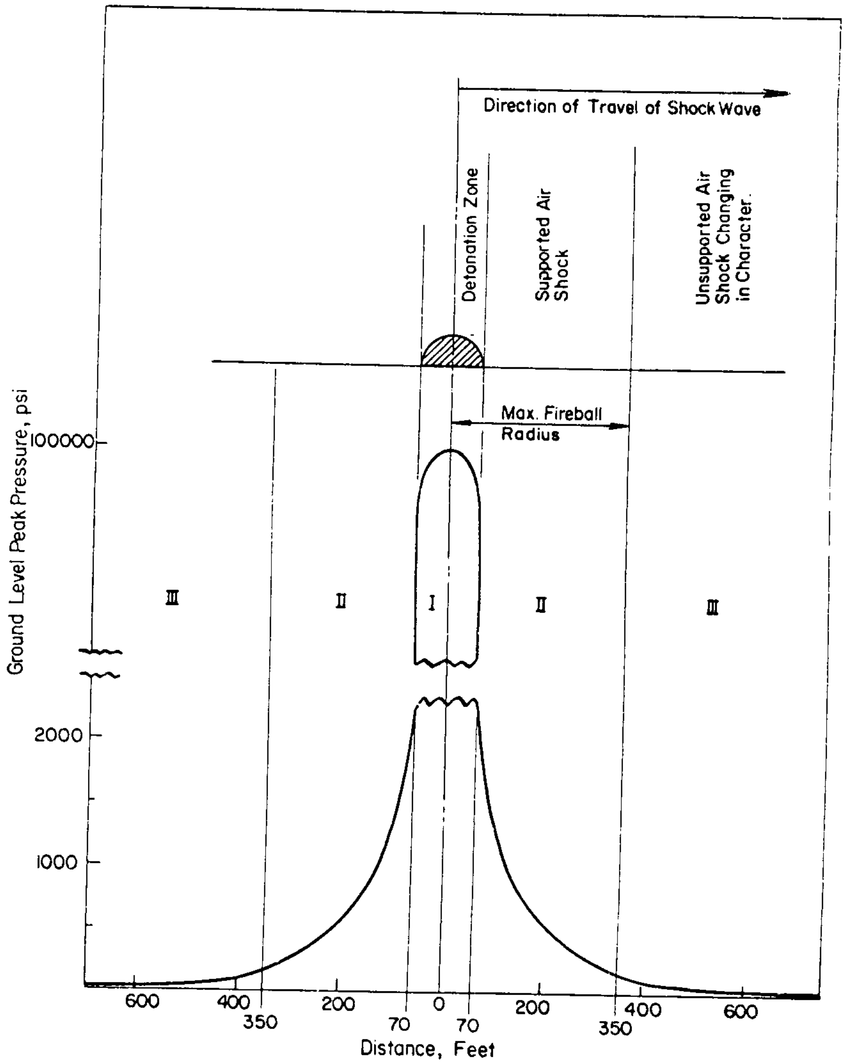


Figure IV-5

TABLE IV-4

EXPECTED PRESSURE CONDITIONS IN A SATURN C-5 REALIZABLE DETONATION

Description	Radial Extent (ft)	Peak Pressure (psi)	Peak Duration (milliseconds)
Liquid Detonating Region	70	100,000	1
Supported Shock Wave	70-350	100-2,000	1-40

(Since the positive impulse (overpressure time integral) of blast waves increases with 1/3 power of the mass of the explosive substance, an extension of the ADL treatment for the total C-5 inventory would yield a radial extent of the liquid detonating region of approximately 120 feet.)

Consider now the likelihood of immersion of the B-4 core in a liquid detonating region. A launch abort and loss of RIFT structural integrity is postulated permitting propellant spillage onto the launch structure. A reduced C-5 realizable detonation inventory of 1,000,000 pounds of homogeneously mixed propellant is assumed. This amount of mixed liquid propellant yields a liquid detonating region whose radius is approximately 70 feet, as shown in Table IV-4. The farthest the core could be from the detonating region is its initial height in the uncollapsed RIFT vehicle of approximately 230 feet.[84] The likelihood of core immersion in the mixed liquid propellant can be roughly estimated by considering the geometry of the system. The fractional solid angle about the core (which can be considered a point since its dimensions are small compared to the problem geometry) subtended by the 70 foot radius of mixed propellant is 0.1 π. The solid angle subtended by all (equally) possible positions of the reactor below its initial height of 230 feet is 2 π steradians. (It is assumed the reactor cannot assume a position anywhere above its initial height). The ratio of the solid angles subtended, an approximate index of the likelihood of immersion,

is 0.1/2, or 5 percent. This occurrence, on the basis of these geometrical considerations, has a probability which is large in terms of probabilities normally considered for major accidents in conventional reactor systems.

The ADL study has shown that a 16 percent compression of graphite occurs at 90,000 psi (approximately 6 percent from a reversible crystal lattice deformation and 10 percent from reduction of intercrystal spaces) for both solid and voided specimens. For ADL specimens of 18 percent void volume (0.093 inch holes drilled axially in the specimen simulating coolant channels), on the other hand, collapse of the holes occurred as low as 9,000 psi. The 18 percent permanent compression of the voided test specimen indicates that nearly complete collapse may be expected for pressures exceeding ~10,000 psi. In fact, the ADL study did conclude that compression of a graphite structure such as NERVA B-! will occur under pressures generated by a liquid propellant detonation, with a possible permanent reduction in volume of an amount equal to the original void volume. Figure IV-6 depicts the stress-strain curve for compression of 18 percent void graphite from the ADL study supporting their judgment.

Further, the likelihood of core compression which could occur (independently) from axial, radial, and a combination of axial and radial loadings of the B-4 structure was also assessed in the ADL study. The period required for distortion of the B-4 structure, based on its natural frequency under various modes of vibration, is reported to be comparable to the predicted duration of the detonation peak pressure, i.e., of the order of a millisecond.

ADL concludes, however, that this time period is short compared to the predicted duration of an excursion, stating that "maximum compression could occur during the detonation, but elastic compression would be relieved prior to the core reaching vaporization temperature." ADL also expects that the anticipated increase in reactivity due to compression would be compensated for by increased neutron leakage due to the creation of gaps between the core and reflector (and between reflector segments) from the expected non-symmetrical nature of the core compression.

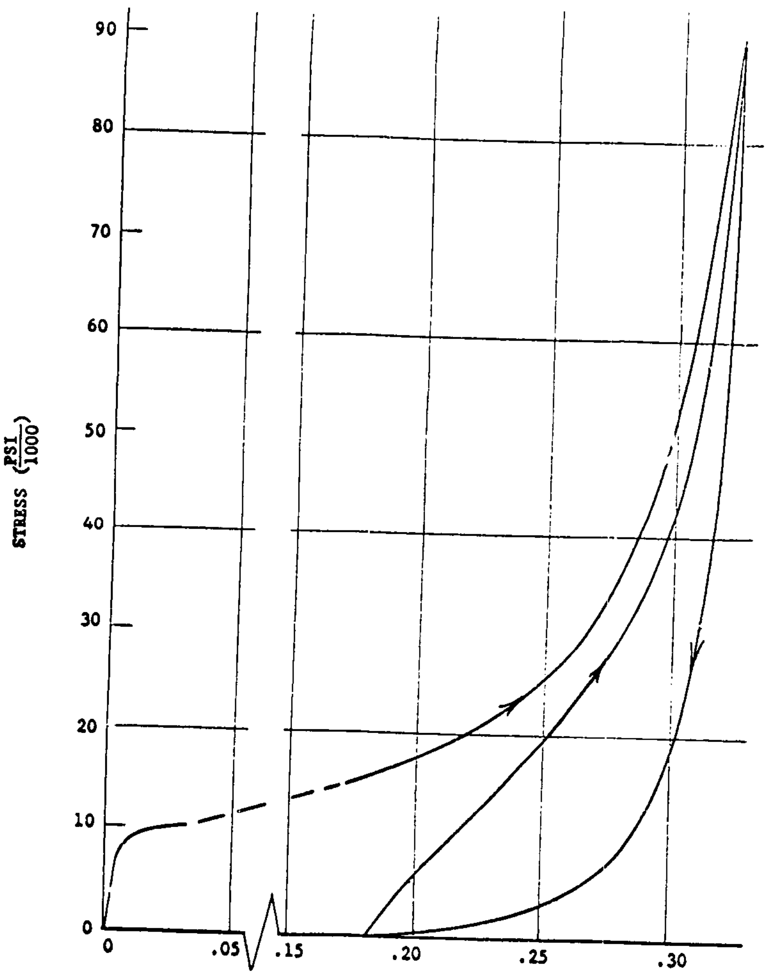


Figure IV-6

STRESS-STRAIN CURVE FOR COMPRESSION

OF GRAPHITE WITH EIGHTEEN PERCENT VOIDS (80)

While elastic compression of the graphite structure requires large detonation pressures (approximately 90,000 psi), collapse of the coolant channels can occur at relatively low pressures (approximately 10,000 psi). After core fracture, the time duration of the pressure wave would appear to be no longer controlling, and even partial compaction of the 26.4 percent void core would yield a substantial release, provided the core remained reflected. Considering this latter stipulation, the reactor may be characterized as a compressible core surrounded by an incompressible Be annulus, the whole contained by an elastic outer shell. Radial loading of the core by a detonation wave would conceivably distort the Be reflector, leading to (partial) loss of reflection and (possible) reactivity compensation. However, only the axial component of the detonation wave, which permits core compression without loss of reflection for the duration of the transient, need be considered. The approximate time for the shock to traverse the core axial length (52 inches) for an assumed sonic velocity of 7,500 ft/sec in graphite at ambient temperature is $\sim \frac{4.3^2}{7500} \cong .575 \times 10^{-3}$ seconds, or essentially instantaneously. If $\Delta K/K$ is assumed proportional to $1/2\ \Delta\rho/\rho$ (LASL approximation), and $\Delta\rho/\rho$ is 0.25, then ΔK is approximately 0.143, or \$19.60. If the limit of \$19.60 were correct, the yield from Figure A-2 indicates that the entire core would be vaporized.

A Los Alamos approximate estimate of the kinetic energy required to crush and compact the core is less than the available energy from the detonating propellant ($\sim .5 \times 10^9$ K cal.). It is assumed, therefore, that the kinetic energy of the axial component of the detonation wave is sufficient to shatter the entire core, and a release of 10^5 MW-sec is assumed for dose calculations for this accident. It is noted that the possibility of the implosion accident is strongly discounted by LASL, although an investigation of core configuration as a function of time is to be made from the ADL data for estimating possible yields.

b. Water Accidents

It is postulated that after a launch abort failure of the reactor destruct occurs and the SN stage falls into an adjacent body of water (e.g., Banana River, or the Atlantic Ocean). Water impact and/or submersion of the core makes a prompt excursion almost a certainty. The treatment of the case is in two parts:

(1) High velocity water injection into the core in the form of droplets of reduced density (followed by "solid water" slugs) upon reactor impact; no reactivity contribution from reflection is assumed.

(2) Infinite water reflection from complete immersion, but no core flooding, such as would be expected should the SN and S-II stages suffer water impact as a structural entity, deferring water entry to the SN stage for the period of the transient.

(a) Water Injection

Second to core compaction, high velocity water injection phenomena are difficult to assess quantitatively due to inexact knowledge of effective droplet water density and velocity within the 94 mil diameter B-4 coolant channels for given impact velocities. On the other hand, the need for exactness may be academic; quite serious releases follow from rather modest assumptions concerning the nature of this accident. It is noted that WANL and LASL are conducting theoretical and experimental programs on the fluid dynamics of core impaction in water. Specifically, core deceleration, water droplet velocity and density as a function of axial distance within coolant channels, are being identified for various impact velocities, core and coolant channel geometries, and angles of entry. The recent WANL analysis is summarized in Figure IV-7,[85] which depicts initial rise (and subsequent flooding) rate as a function of impact Reynolds number. Table IV-5 summarizes the initial rise rate (jetting velocity), core traverse time for the 4.3 ft. high B-4 core, and the resulting reactivity insertion for a number of impact velocities.

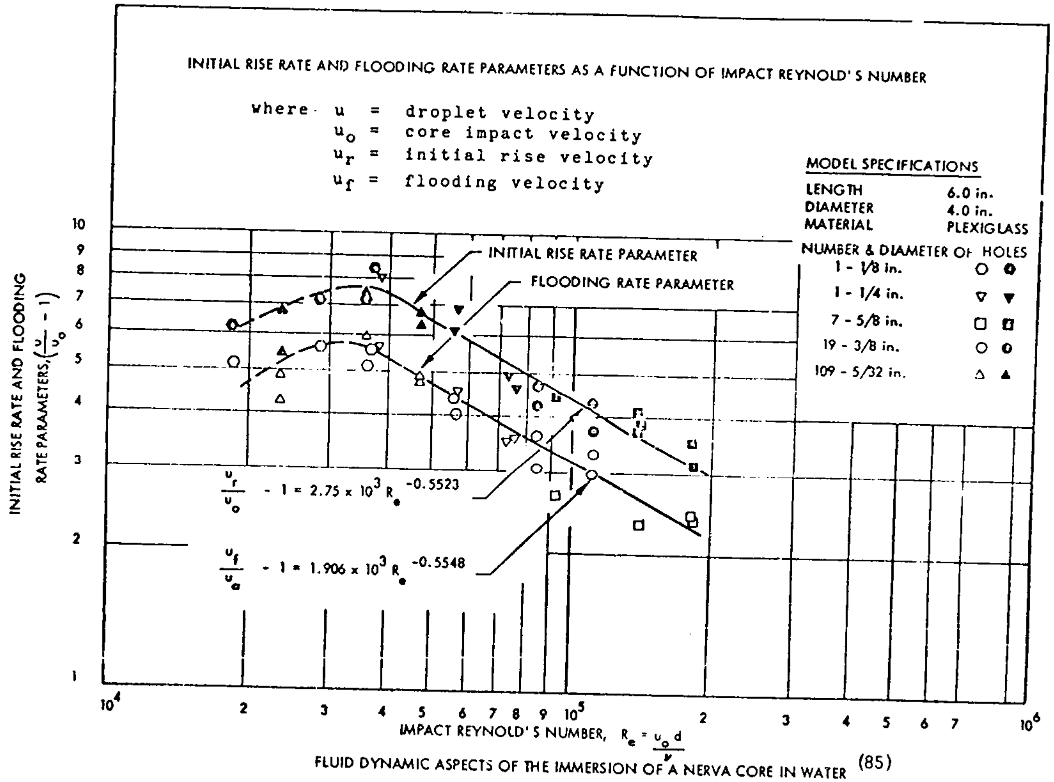

INITIAL RISE RATE AND FLOODING RATE PARAMETERS AS A FUNCTION OF IMPACT REYNOLD'S NUMBER
where u = droplet velocity
u_o = core impact velocity
u_r = initial rise velocity
u_f = flooding velocity
MODEL SPECIFICATIONS
LENGTH 6.0 in.
DIAMETER 4.0 in.
MATERIAL PLEXIGLASS
NUMBER & DIAMETER OF HOLES
1 - 1/8 in.
1 - 1/4 in.
7 - 5/8 in.
19 - 3/8 in.
109 - 5/32 in.
INITIAL RISE RATE PARAMETER
FLOODING RATE PARAMETER
$\frac{u_r}{u_o} - 1 = 2.75 \times 10^3 R_e^{-0.5523}$
$\frac{u_f}{u_o} - 1 = 1.906 \times 10^3 R_e^{-0.5548}$
INITIAL RISE RATE AND FLOODING RATE PARAMETERS, $(\frac{u}{u_o} - 1)$
IMPACT REYNOLD'S NUMBER, $R_e = \frac{u_o d}{\nu}$
FLUID DYNAMIC ASPECTS OF THE IMMERSION OF A NERVA CORE IN WATER (85)

Figure IV-7

(A coolant channel diameter of 0.094 inches is assumed and a droplet density 1/10 normal water density.)*

TABLE IV-5

CORE IMPACT VELOCITY AND B-4 REACTIVITY

Core Impact Velocity (feet/sec)	Jet Velocity (feet/sec)	Axial Traverse Time (milliseconds)	Estimate of Reactivity Insertion ($/sec)
50	435	10	1100
100	600	7.16	1535
125	705	6.1	1800
150	780	5.5	2000

Thus, it is seen from Figure A-7 (Appendix A) that, for the minimum 50 ft/sec core impact velocity, corresponding to a freefall of about 39 feet, an insertion of $1,100/sec and a yield in excess of 10^{22} fissions results. A more accurate estimate of energy release, however, is obtained from Figure A-2, since the 1/10 droplet water density yields a maximum of $12 ($11 over prompt critical). The yield for a total insertion of this magnitude is seen (Figure A-5) to be $\sim 4 \times 10^{21}$ fissions with a kinetic equivalent of ~200 pounds H.E. From Figure A-6, the energy stored in the form of liquid and vapor is $1.75 \times 10^{20} + 7 \times 10^{20} = 8.75 \times 10^{20}$ fissions. For the assumed latent heat of vaporization (172 Kcal/mole $= 1.98 \times 10^{15}$ fissions/gm), the available energy could vaporize at most $8.75 \times 10^{20}/1.98 \times 10^{15} = 4.42 \times 10^{5}$ gm or

*DSN calculations performed by LASL on the reactivity worth of various hydrogen densities in the core disclose that 1/10 normal water density implies an excess K of $12.

~ 34 percent of the core. This yield of 4×10^{21} fissions is an overestimate since water at the core end would cause drastic spatial and spectral effects; the axial distribution would be grossly peaked, producing a yield which is less than that for the assumed cosine distribution on which the RAC analyses of this study are based. In fact, it is expected that the end or a portion of the core would be disintegrated upon impact.

The yield assumed for dose purposes is 3×10^{21} fissions, or $\sim 10^{5}$ MW-sec. The distribution of material resulting from this occurrence is highly uncertain. Undoubtedly, a significant portion of the core material would be vaporized and released to the atmosphere. Another significant fraction would be carried down into the water as large pieces, scattered over some large area.

(b) Infinite Water Reflection

The reactivity worth of (infinitely) thick water against the end of the core has been inferred from thick polyethylene measurements in mockup criticals on KIWI B-1A to contribute $2.17; around and outside of the pressure shell to contribute $2.60; and about 8 inches from the plenum end of the core outside the pressure vessel to contribute $0.23. The total insertion is $5.00 ($4.00 above prompt critical), yielding for a just-critical state upon immersion 5×10^{20} fissions for the case of no internal flooding. The energy stored in the form of liquid and gas again obtained from Figure A-6 is $1.12 \times 10^{20} + 0.7 \times 10^{20} = 1.82 \times 10^{20}$ fissions. The available energy could vaporize at most 7.1 percent of the core. No melting is expected. The release is conservative to the extent that full reflection cannot be obtained instantaneously.

c. Core Deformation from Land Impact

No experimental data are at hand for estimates of deformation from scale models. An estimate by LASL of the kinetic energy obtained from a fall of 150 feet indicates that this is sufficient to compact all flow channel voids. The estimate makes no allowance for permanent yield of the pressure vessel or reflector, or extreme distortions of the core geometry. Again it is assumed that $\Delta K/K \sim 1/2\, \Delta\rho/\rho$; for $\Delta\rho/\rho$ = .25, ΔK is ~\$19.60. For a 230 ft. fall, the final velocity is 122 feet/sec and for a core diameter of 3 feet, the time for a shock to traverse the core diameter would be 2.46×10^{-2} seconds. Should core compression leading to a reactivity change be 1/4 of the LASL estimate, the insertion rate is $4.9/2.46 \times 10^{2}$, or ~\$200/sec. The yield from Figure A-8 is 1.3×10^{21} fissions. For the step insertion limit of \$4.90, the yield from Figure A-2 is more appropriate, or 7×10^{20} fissions. Core vaporization, computed from the energy partition of Figure A-6, is 11 percent. Figure IV-8, a plot of core temperatures and percent of core molten versus total fissions from RAC analyses discloses ~80 percent of the core would be liquefied.

d. Liquid Hydrogen Injection

It is assumed that the accident results from a sudden flow of liquid hydrogen into the reactor core due to gross engine malfunction. It is further assumed that hydrogen in the core is worth about \$2 per pound at the rate of 70 pounds/sec pumping rate with no delay. In addition, it is postulated that the hydrogen enters a core which is at ambient temperature, and that no choking in the nozzle, reflector, or core passages occurs. The insertion rate is thus \$140/second under these limiting conditions, and the yield obtained from Figure A-8 is 9×10^{20} fissions (~3×10^{4} MW-sec). The kinetic equivalent is ~13 pounds H.E. (Figure A-5), and percent of core molten is 86 percent (Figure IV-8).

This energy release is considered an overestimate for the following reasons:

(1) Additional quenching (shutdown of nuclear transient) from fuel particle vaporization is expected prior to graphite vaporization and core thermal expansion; this contribution is neglected.

(2) Liquid hydrogen injection at the plenum end would be attended by highly skewed axial distribution, peaked at

NERVA B-4 CORE STATE VERSUS ENERGY RELEASE

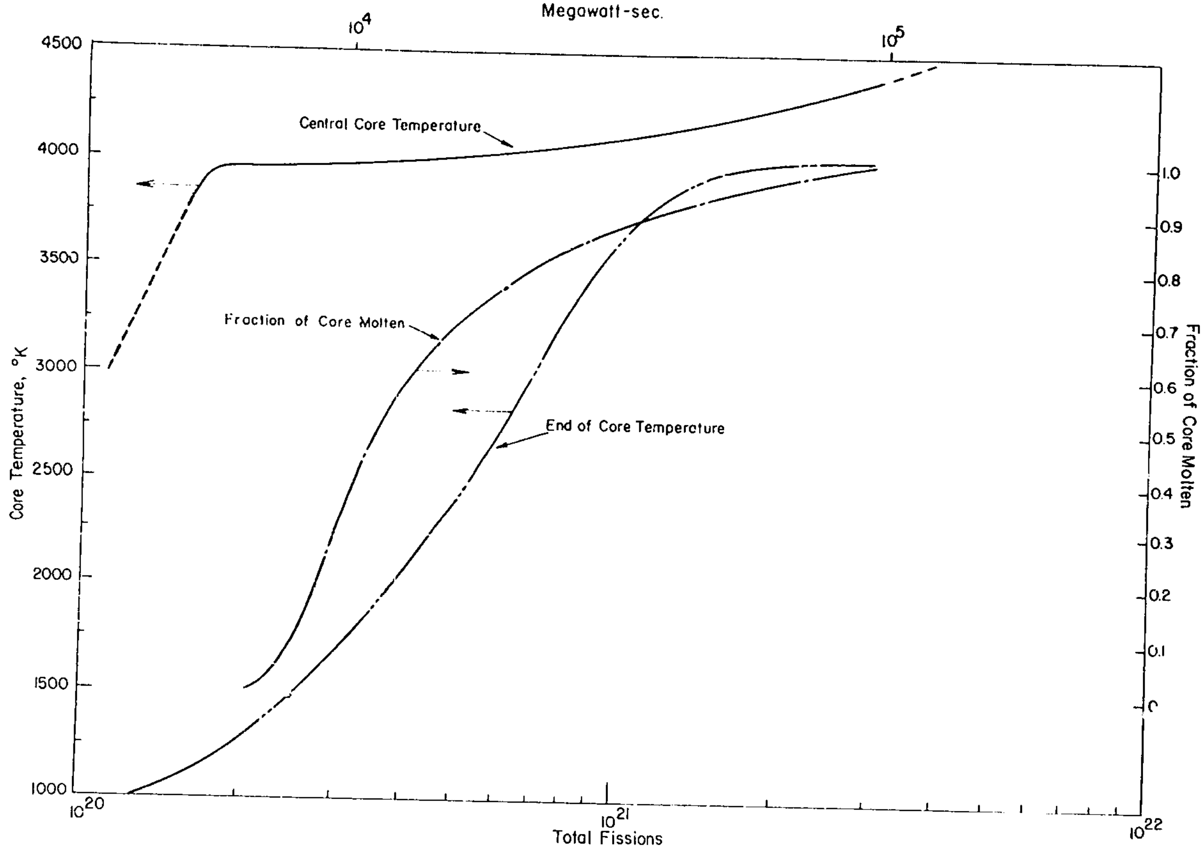


Figure IV-8

the plenum end. RAC exploratory calculations for such spatial distributions show a lower fission yield when compared to a cosine distribution for the same reactivity insertion, as discussed previously.

(3) It is to be expected that the injection of liquid hydrogen into nozzle, reflector and core at ambient temperature under conditions of pump or control malfunction will result in surging, erratic, and non-homogeneous flow of liquid and gaseous hydrogen. It is more realistic to expect that a lessened hydrogen density in the core would obtain under the conditions of this accident, with a ramp insertion due to less hydrogen per unit time flowing through the core.

It is assumed, therefore, arbitrarily that the release is of the order of 3×10^{20} fissions ($\sim 10^4$ MW-sec).

e. Control Vane "Runout"

The improbable simultaneous failure of the servocontrol system, the scram circuit, and safety mechanisms of all control vanes is assumed, coincident with the occurrence of a signal which turns all drums "out" at the maximum possible reactivity insertion rate. The transient is assumed to start with the core at ambient temperature; three drum speeds have been analyzed by LASL, 22 1/2°, 45°, and 90° with all vanes moving together. From Figure A-10, the releases for these rotational velocities are seen to be 4.95×10^{19}, 7.53×10^{19}, and 9.92×10^{19} fissions, respectively. Thus, the estimate for the extreme case (90°/sec) is $\sim 10^{20}$ fissions. Thus, although (from Figure IV-8), 1.8×10^{20} fissions are required to raise the central part of the core to vaporization temperatures, this value is approached only after more than 500 milliseconds. Thus, no graphite explosion is expected to occur even though power levels following this nondestructive burst approach 3950 megawatts. The spike power level for this extreme case is estimated to be about 7.5×10^{21} fissions/sec. Table IV-6 summarizes these data for the 90°/sec case, and also includes the 22 1/2° and 45°/sec cases.

TABLE IV-6

FISSION YIELDS FOR SEVERAL
CONTROL VANE RUNOUT RATES

	Drum Rotational Velocities		
	22 1/2° /sec	45° /sec	90° /sec
Total Yield, Fissions	4.95×10^{19}	7.53×10^{19}	9.92×10^{19}
Spike Yield, Fissions/sec	1.84×10^{21}	3.68×10^{21}	7.5×10^{21}
Central Power, MW	1610	1940	3950
Central Core Temperatures (after 500 m secs), °K	~3000	~3500	~3950

f. Effect of Other Factors

As stated earlier, the effect of the coated fuel particles, which is ignored in the RAC treatment of the cases considered, undoubtedly is of consequence although the magnitude of the effect cannot be stated with precision. The effect has been studied through the use of the Los Alamos Necklace code, a calculational routine which permits a detailed description of the energy deposition in a UC_2 fuel bead, and the heat conduction through the coating and into the graphite matrix. This code, not presently in operational status, solves the transient, one-dimensional heat conduction equation in spherical geometry. The spherical UC_2 particle, the coating, and the surrounding graphite matrix are all separately described with their appropriate material properties. Eighty-six percent of the energy deposition is uniformly deposited in the UC_2 fuel, the remaining 14 percent is deposited in the pyro-carbon coating. (It has been computed that 14 percent heating occurs in the coating due to heating from direct fission fragments having a range of ~17 microns). Further, perfect conduction, i.e., physical contact is assumed between the UC_2 fuel and its pyro-carbon coating. Temperatures at various radii of the spherical shells are then computed as a function of time for the instantaneous uniform energy deposition. Pressure effects attending energy releases are not treated in the Necklace code.

A pertinent result is the temperature differential across the pyro-carbon coating. This ΔT has been determined to be $3^{\circ}C$ for steady state operation at 10^3 megawatts; at 10^6 megawatts, it is $3,000^{\circ}C$. The maximum powers which result from various NERVA transients are identified in Figure A-8. In the TREAT experiments, the ΔT is computed (with reasonable accuracy) to be about $200^{\circ}C$ with the observed result that the beads have little influence. For NERVA B-4 transients of \$0.60, the peak power is $\sim 10^5$ megawatts, the $\Delta T \sim 300^{\circ}C$, and little effect is anticipated. An additional factor of ten in peak power, however, achieved from an insertion of \$1.80, yields a ΔT of $3,000^{\circ}C$. UC_2 vaporization would then be expected (before heat loss to the coating and matrix), resulting in high internal pressures and probable shattering of the fuel bead and contiguous graphite matrix.

Thus, for transients up to ~ \$1.50 (ΔT's = $1,800^{\circ}C$) the pyro-carbon coated beads have essentially no influence. Above ~\$1.50, the internal vaporization of UC_2 and resulting pressures are expected to become significant and may possibly contribute to the shutdown.

A summary of the integrated power resulting from the cases treated above is listed in Table IV-7.

2. Release of Fission Products

In addition to the uncertainties in nuclear parameters pertaining to the NERVA reactor, the release of fission products following an excursion is as yet not well defined. The quantitative evaluation of the release is dependent not only upon the total number of fissions, but also upon the temperatures achieved, the exposed fuel surface, the state of the matrix and of the fuel particle coating, as well as the chemical nature of the individual fission product elements.

Considering those doses resulting from environmental transport of radioactive materials, it is apparent that substantial retention of fission products in the intact core would essentially eliminate all radiation problems except those concerned with the intact, radioactive reactor. On the other hand, it is recognized intuitively that the injection of substantial energies into the core in very short

TABLE IV-7

KIWI B-4 ACCIDENT SUMMARY
(Reactivity Insertions and Resulting Excursions)

Description	Amount ($ over prompt)	Rate ($/sec)	Energy Release (fissions)	Core Damage	Kinetic Energy lb H.E.	Assumptions or Comments
Immersion in detonating propellant, core compression	19.60	---	$>10^{22}$	100% Vaporized	$>10^{3}$	Complete core compression
Water impact, water droplet core injection	11.0	(<1,000)	4.0×10^{21}	~34% Vaporized ~100% Liquefied	~120	Droplet water density assumed 1/10 normal H_2O density
Complete water reflection (no core flooding)	4.0	---	5.0×10^{20}	~7% Vaporized ~69% Liquefied	~7	
Land impact, free fall of core from stage height of ~230'	4.9	(200)	7.0×10^{20}	~11% Vaporized ~80% Liquefied	~10	Assumption $\Delta k/k \sim 1/2\ \Delta\rho/\rho$
LH_2 core injection	---	140	9.0×10^{20}	~15% Vaporized ~86% Liquefied	~13	
Control vane runout (12 drums at 90°/sec)	---	3.64	9.92×10^{19}	0 Vaporized 0 Liquefied	0	Comment: Central melting temperatures reached after ~500 msecs.

time periods will produce conditions which are conducive to the release of fission products. These conditions may include vaporization of a substantial part of the core, and fragmentation or liquefaction of part of the core with subsequent release of fission products by diffusion at high temperatures, or by deposition of particles at a distance from the site of the release.

Three sources of information are available which bear on the problem of release from graphite fuel elements. The first source is the General Atomics development effort on HTGR fuel elements, a graphite dispersion of uranium-thorium carbide particles coated with 60 micron pyrolytic carbon; the second source are the investigations by LASL on the effect of high temperatures on ROVER fuel elements; and the third is the joint WANL-LASL-ANL study of the behavior of NERVA fuel elements under transient conditions in the TREAT reactor.

HTGR fuel development and testing effort has been described in a series of Quarterly Progress and Topical Reports.(86,87) Although much of the work has been conducted at temperatures below those of interest in this study, some semi-quantitative observations can be usefully drawn from the General Atomics effort. The first observation is that a few thermal cycles to temperatures above the melting point of the fuel (~2,500°C) were sufficient to crack the fuel particle cladding and permit complete recovery of noble gas activities for a material balance in release studies.(88) The second observation is that a single short-time exposure at 3,000°C was sufficient to completely release noble gases following cooldown of the fuel element.(89)

Los Alamos has conducted research on the release of fission products from graphite, and on the behavior of the pyro-carbon-coated fuel particles following various heating cycles. The latter study(90) has indicated that, at temperatures achieved in short-period high power transients, the pyro-carbon coating disperses into the graphite matrix and the fuel tends to disperse also. Thus, such conditions would appear to result in fuel closely resembling the uncoated fuel dispersion elements formerly employed in KIWI cores.

In another LASL study of the release of fission products from uncoated fuel elements,(91) Bryant indicated that about 80 percent of the gross fission product mixture was lost on heating for five minutes at 3,200°C. The loss by element is indicated in Table IV-8, in which it may be seen that the only elements substantially retained in the fuel were zirconium, niobium, molybdenum, technetium, ruthenium and rhodium.

TABLE IV-8

FISSION PRODUCT LOSS FROM GRAPHITE FUEL ELEMENTS(91)
(After Five Minutes at 3,200°C)

Group	Elements	Percent Loss
I	All elements up to Br plus Rb, Sr, Ag, Cd, In, Sn, Sb, Cs, Eu	~99.9
II	Kr, Pd, Te, I, Xe, Ba, Sm	~99
III	Y, La, Ce, Pr, Nd, Pm	~90
IV	Zr, Nb, Mo, Tc, Ru, Rh	~0

The behavior of pyro-carbon fuel coating noted above in LASL furnace studies has been tentatively confirmed in recent TREAT tests conducted by WANL and LASL.(92) Irradiation tests of NERVA prototype fuel elements in TREAT have indicated that, for coated fuel materials, fragmentation and release of fission products occurs only above an energy deposition equivalent to several thousand MW-sec in NERVA. Below this somewhat indefinite value, no more than a very small fraction of the volatile fission products are released. Further tests are planned to refine present understanding of the mechanism of fuel particle behavior under short-period transients.

In summary, it appears likely that excursions of more than a few thousand MW-sec, resulting in central core temperatures well above 3,000°C as shown previously in Figure IV-8, would result in the complete release of volatile elements (Groups I, II and III in Table IV-8) as delineated by the LASL study[91] and these elements are assumed to be released in the following hazard evaluation. Although the pyro-carbon fuel coating was originally intended to inhibit the oxidation and hydrolysis of UC_2 during fuel element storage and transit, some study has already been devoted to the use of this coating (perhaps thicker, and made of pyrographite) as an inhibitor of fission product release from the fuel particles.

3. Selection of Accidents for Evaluation

An infinite number of nuclear accidents can be hypothesized for the nuclear rocket and associated systems. These range from nuclear excursions of very low power to those which completely vaporize and disperse the core. It is necessary to examine all of the accidents, since the magnitude of the nuclear excursion alone is not necessarily a measure of the hazard to the environment. To provide a meaningful indication of the range of problems faced in the launch site environment, it is felt that a few situations can be postulated which will provide a satisfactory basis from which more refined estimates can be extrapolated when better data are available with respect to both source and environment.

From the environmental point of view, a major consideration derives from the locus of the release; that is, whether to the atmosphere or the hydrosphere, since the mechanisms of material transport and the resulting hazards are vastly different in both magnitude and immediacy. An additional factor of significance in the environmental transport is the initial spatial distribution of the toxic agents which derives either from nuclear or from chemical energy sources. On the basis of both the transient analysis data and the environmental factors, it is felt that treatment of three hypothetical occurrences should provide a satisfactory indication of the type and range of problems associated with launch site hazards. The details of the causal events for each of the three events are not specified, since it is not the purpose of this study to treat specific accidents - but rather classes of accidents.

Two of these accidents are presumed to occur on land, at least to the extent that the release of fission products occurs to the

atmosphere. The first, a so-called "nuclear criticality accident," is assumed to occur as a result of any of several initiating mechanisms (such as control vane runout, shallow water or land impact, liquid hydrogen introduction, etc.) which does not involve a concurrent release of chemical energy. In view of the uncertainty in energy release for a given reactivity insertion, as well as in modes of insertion, a release of $\sim 10^4$ MW-sec (3×10^{20} fissions) is chosen to represent this class of accidents. This value is almost certainly above the threshold for fission product release from the reference fuel particles, and may in fact involve the vaporization of a portion of the core, although the extent of the core vaporization is not yet firmly established.

As indicated in the prior discussion, estimates for excursion magnitude upon water injection into the core are in the order of 10^5 MW-sec. With this magnitude of energy release, violent disassembly of the core would almost certainly occur before the entire reactor entered the water. Any cloud rise accompanying this accident would probably be small and an appreciable but presently undetermined fraction of the fission products would enter the atmosphere. This accident, of which the consequences could be quite serious if it should occur in the immediate vicinity of the launch site, requires additional study which has not been possible for this preliminary report. Much depends upon the site of impact and the degree and type of fragmentation upon impact. As a preliminary estimate, it can be assumed that the doses calculated in Section IV-C below for the "nuclear criticality accident" should be multiplied by a factor of ten.

The second class of accidents is intended to deal with those malfunctions involving the concurrent release of both nuclear energy and chemical energy. These are the accidents which might occur after the vehicle is fueled, when propellant fires or explosions are possible. Again, a numerical evaluation of the credibility of this occurrence, or a detailed chronology, is not felt to be warranted in view of the many unknowns. This class of accident might occur as a result of a booster explosion on, or shortly above, the pad concurrently with a nuclear excursion, or by a fallback accident on land which involved the failure of a destruct system and an explosion and excursion on impact. In any event, for this study, this class of accidents is represented by an excursion of about 10^5 MW-sec (3×10^{21} fissions) in magnitude accompanied by the release of chemical energy from propellants equivalent to 10^6 pounds of high explosive (see Section IV-B).

The third class of accidents is representative of those resulting in the injection into water of the fission product inventory from an excursion. As discussed in earlier sections of the report, water is plentiful in the Cape Canaveral environment, and also is an extremely effective medium for reactivity insertion in NERVA reactor cores. Here again, however, there are many uncertainties which preclude precise definition of accidents involving immersion of the reactor in water, such as the attitude and velocity of the reactor on impact, the depth of the water and the degree of immersion or reflection, the change in state of the core as it penetrates the air-water interface, etc. Since releases to the atmosphere are already covered by the first class of accidents considered, this class describes the effect of retention of fission products in surface waters at the Cape Canaveral area. Again the magnitude of the nuclear energy release is assumed to be approximately 10^4 MW-sec, and all fission products except the noble gases are presumed to remain in the aqueous phase. Again, it should be noted that an energy release some ten times greater may occur upon injection of water into the reactor core. A substantial fraction of the fission products in this event would not be retained in the aqueous phase, but released to the atmosphere, due to the violent disassembly of the reactor core in such a case.

Each of these classes of accidents is treated in detail in the sections that follow, with some comments made on the effect of various assumptions on the resulting doses.

C. NUCLEAR EXCURSION ACCIDENT

1. General

This accident is defined as one which results in a nuclear excursion with an integrated power of 3×10^{20} fissions (approximately 10^4 MW-sec) and which is unaccompanied by chemical or other energy. The reactor is assumed to be at or close to ground level and no appreciable rise of the released fission product materials is assumed to occur. From

the point of view of downwind transport of released radioactive materials, the case of no cloud rise yields the largest doses. It is difficult to support an appreciable cloud rise in the absence of additional thermal input to the system beyond that associated with the nuclear excursion.

The accident may occur in the nuclear assembly building, the vertical assembly building, or the launch pad or at any location in between. For the purpose of this analysis, the accident is considered to occur at Pad A as shown in Figure IV-9, although the dose isopleths derived below can be transposed to any outdoor location at which the accident is presumed to occur.

2. Source Description

a. Magnitude of Excursion

As indicated in prior discussion, the magnitude of the nuclear energy release associated with a given insertion of reactivity is imprecise at present. A more precise definition of excursion magnitude depends not only upon the hypothesized insertion of reactivity, but also upon several parameters including the temperature coefficient of reactivity, the equation of state of graphite, and the physical behavior of the core for a given energy deposition as discussed above.

In view of the present uncertainties, it is felt that no greater precision should be attached to the energy release than the nearest order of magnitude for such accidents which in this case is considered to approximate 10^4 MW-sec (3×10^{20} fissions), that is, any excursion between 5×10^3 and $<5 \times 10^4$ MW-sec.

b. Fission Product and Toxic Materials Release

At the present time there is no definition of the state of the core following a transient resulting in an integrated power of 10^4 MW-sec. In an early report,[93] LASL indicated that 3×10^{20} fissions would result in the vaporization of about 15 percent of a loaded core. A subsequent treatment by LASL[77]

COMPLEX 39 SITE LOCATION PLAN

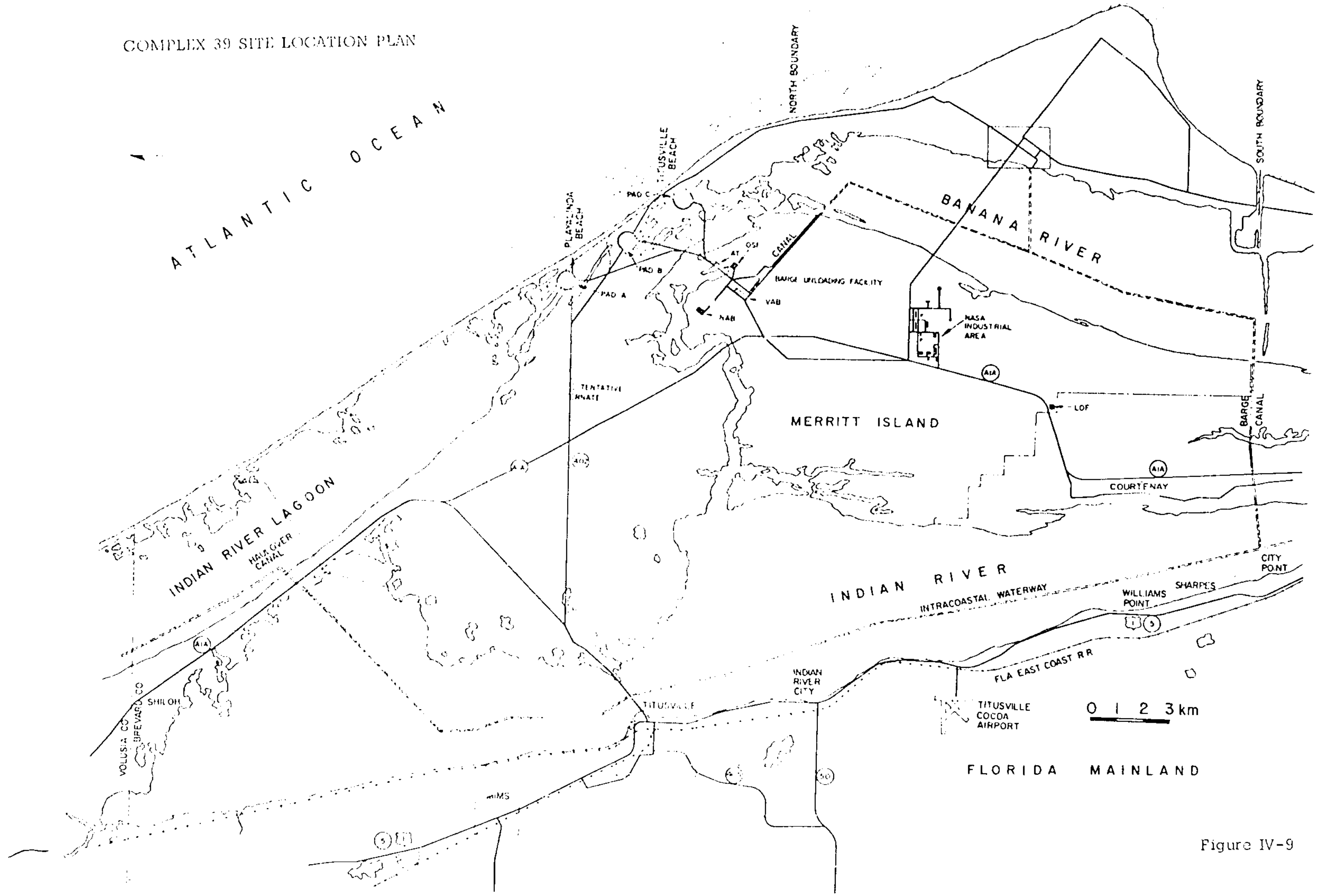


Figure IV-9

indicated that 2/10 percent of the core would be vaporized by an excursion resulting in this total energy release. Recent experiments[92] have indicated a loss of approximately 20 percent of all of the core material for excursions of this magnitude. Although the behavior of the core is uncertain as indicated by the information cited above, certain assumptions can be made which will indicate the degree of hazard associated with a limiting range of accidents of this magnitude. Two cases are treated in general: the first considering the release of volatile elements* and noble gases only; the second considering a release of 20 percent of the residual nonvolatile source activity in addition to the first.

Beryllium is present in the reactor assembly as reflector material. However, there is no basis for assuming a release of beryllium as a result of an accident of the type hypothesized in this case, since the temperatures and pressures resulting are not sufficiently high to cause vaporization of beryllium or dispersion of the massive beryllium metal in sufficiently fine fragments to cause an inhalation problem.

Volatile elements are assumed to be released in gaseous form and any condensation that occurs following their release from the core is assumed to occur on condensation nuclei present in the air whose size is sufficiently small so that the behavior of the condensed materials is essentially that of vapors or gases. The residual source is considered to remain in the intact reactor core or parts thereof constituting direct radiation hazard, but not contributing to material transported by the atmosphere.

c. Fission Product Inventories

Fission product inventory data have been obtained from Westinghouse Astronuclear Laboratory[94] and are reproduced in Table IV-9. Values given in this table for volatile elements have

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*Note that volatile elements in this case are listed in Table IV-8 as Groups I, II and III and in Figure IV-10.

TABLE IV-9

ACTIVITY (μc) FROM 0.1 MIN. BURST OF 10^{10} THERMAL FISSIONS

(The activity is set equal to zero if it is less than 10^{-10} μc)

ISOTOPE	TIME AFTER BURST (MIN.) 0.1	1	3	6	10	30	60	100	300	600	1000	3000	6000	10, 000
Zn^{72}	1.772 - 7	1.771 - 7			1.768 - 7			1.729 - 7			1.385 - 7			1.516 - 8
Ga^{72}	0	0			0			0			0			0
Ga^{73}	1.148 - 5	1.166 - 5			1.142 -5			9.232 - 6			1.103 - 6	9.897 - 9	0	0
Ga^{74}	1.395 - 3	1.288 - 3			5.788 - 4	9.788 - 5	6.807 - 6	1.947 - 7	0		0			0
Ge^{77}	1.427 - 4	1.426 - 4			1.413 - 4			1.289 - 4			5.132 - 5	6.653 - 6	3.101 - 7	5.196 - 9
Ge^{78}	4.955 - 3	4.931 - 3			4.693 - 3			2.860 - 3	9.519 - 4		2.013 - 5	3.374 - 10	0	0
As^{77}	6.993 - 5	6.995 - 5			7.015 - 5			7.186 - 5			7.438 - 5			6.507 - 6
As^{78}	1.887 - 6	3.564 - 5			3.519 - 4			1.963 - 3	1.610 - 3	4.730 - 4	6.375 - 5	1.212 - 9	0	0
As^{79}	1.936 - 1	1.806 - 1			9.030 - 2	1.935 - 2	1.920 - 3	8.816 - 5	0	0	0			0
Se^{79m}	1.717 - 3	2.915 - 2			1.009 - 1	3.244 - 2		1.552 - 4	0		0			0
Se^{79}	0	0			0			0			0			0
Se^{81m}	4.599 - 3	4.549 - 3			4.078 - 3			1.365 - 3	1.199 - 4	3.123 - 6	2.382 - 8	0		0
Se^{81}	2.229 - 1	2.156 - 1			1.549 - 1	7.480 - 2		7.032 - 3	1.798 - 4	4.612 - 6	3.517 - 8	0		0
Se^{83}	2.745 - 1	2.677 - 1			2.086 - 1			1.720 - 2	6.711 - 5	1.636 - 8	0			0
Se^{84}	8.614 -	7.130			1.077	1.615 - 2	2.966 - 5	6.670 - 9	0		0			0
Se^{85}	5.011 + 1	1.920 + 1	2.277	9.300 - 2	1.308 - 3	0		0			0			0
Br^{83}	4.126 - 2	4.226 - 2			5.050 - 2			5.754 - 2	2.334 - 2	5.509 - 3	7.993 - 4	5.290 - 8	0	0
Br^{84}	1.077 - 1	2.503 - 1			7.182 - 1			1.141 - 1	1.458 - 3	2.106 - 6	3.365 - 10	0		0
Br^{85}	5.845 - 1	6.424			1.467	1.446 - 2	1.414 - 5	1.373 - 9	0		0			0
Kr^{83m}	9.323 - 3	9.500 - 3			1.148 - 2			3.216 - 2			2.742 - 3	2.483 - 7	0	0
Kr^{85m}	2.395 - 2	3.364 - 2			1.350 - 1			1.199 - 1			1.125 - 2	5.908 - 5	2.239 -8	0
Kr^{85}	0	0			0			0			0			0
Kr^{87}	9.964 - 1	9.885 - 1			9.125 -1			4.101 - 1	6.936 - 2	4.823 - 3	1.367 - 4	0		0
Kr^{88}	6.635 - 1	6.610 - 1			6.369 - 1			4.394 - 1			1.067 - 2	2.795 - 6	0	0
Kr^{89}	4.431 + 1	3.646 + 1			5.191	6.821 - 2	1.028 - 4	1.774 - 8	0		0			0
Rb^{87}	0	0			0			0			0			0
Rb^{88}	1.290 - 3	2.405 - 2			2.086 - 1			4.763 - 1	2.153 - 1	6.245 - 2	0			0
Rb^{89}	9.993 - 2	1.693 + 1			6.146			1.307 - 1	1.610 - 5	0	0			0
Rb^{90}	6.588 + 1	5.229 + 1			5.189	3.058 - 2	1.383 - 5	4.804 - 10	0		0			0
Sr^{89}	2.057 - 3	2.057 - 3			2.057 - 3			2.055 - 3			2.038 - 3			1.870 - 3
Sr^{90}	1.557 - 7	2.648 - 6			1.128 - 5			1.224 - 5			1.224 - 5			1.223 - 5
Sr^{91}	3.117 - 1	3.114 - 1			3.081 - 1			2.768 - 1			9.464 - 2	8.752 - 3	2.457 - 4	2.094 - 6

ISOTOPE	0.1	1	3	6	10	30	60	100	300	600	1000	3000	6000	10,000
Sr^{92}	1.022	1.018			9.792 - 1			6.662 - 1			1.410 - 2	2.719 - 6	0	0
Sr^{93}	2.401 + 1	2.218 + 1			1.007 + 1	1.742	1.253 - 1	3.747 - 3	0		0			0
Sr^{94}	1.263 + 2	7.818 + 1	2.691 + 1	5.436	6.442 - 1	1.505 - 5	0	0			0			0
Y^{90}	0	0			0			0			0			0
Y^{91m}	1.270 - 4	2.398 - 3			2.352 - 2			1.293 - 1			6.224 - 2	5.756 - 3	1.616 - 4	1.377 - 6
Y^{91}	5.181 - 8	9.826 - 7	3.048 - 6		1.024 - 5			9.748 - 5			6.022 - 4			8.053 - 4
Y^{92}	1.639 - 4	3.104 - 3			3.143 - 2			2.255 - 1			8.112 - 2	1.939 - 4	1.330 - 8	0
Y^{93}	1.349 - 3	2.465 - 2			1.784 - 1			2.792 - 1			1.016 - 1	1.078 - 2		4.182 - 6
Y^{94}	2.205 - 1	3.290			6.342			2.824 - 1	2.762 - 4	8.448 - 9	0			0
Y^{95}	1.930 + 1	1.813 + 1			9.715	2.428	3.035 - 1	1.896 - 2	1.807 - 8	0	0			0
Zr^{93}	0	0			0			0			0			0
Zr^{95}	7.153 - 6	1.318 - 4			1.031 - 3			2.065 - 3			2.053 - 3			1.883 - 3
Zr^{97}	1.806 - 1	1.805 - 1			1.794 - 1			1.688 - 1			9.150 - 2	2.352 - 2	3.062 - 3	2.019 - 4
Nb^{93m}	0	0			0			0			0			0
Nb^{95m}	4.049 - 4	4.049 - 4			4.044 - 4			3.998 - 4			3.561 0 4	2.755 - 4	1.874 - 4	1.121 - 4
Nb^{95}	3.560 - 10	5.289 - 9			5.536 - 8			5.526 - 7			5.193 - 6	1.356 - 5		1.212 - 4
Nb^{97m}	5.739	3.156			1.782 - 1			1.622 - 1			8.792 - 2	2.260 - 2	2.942 - 3	1.940 -4
Nb^{97}	2.758 - 3	3.949 - 2			8.895 - 2			1.375 - 1			9.864 - 2	2.536 - 2	3.301 - 3	2.176 - 4
Nb^{98}	3.841 - 2	3.795 - 2			3.366 - 2			1.014 - 2	7.052 - 4	1.293 - 5	6.167 - 8	0		0
Nb^{100}	6.482 + 1	5.265 + 1			6.584	6.487 - 2	6.344 - 5	6.159 - 9	0		0			0
Nb^{101}	1.690 +2	9.054 + 1	2.263 + 1	2.829	1.768 - 1	1.684 - 7	0	0			0			0
Mo^{99}	4.742 - 2	4.742 - 2			4.734 - 2			4.661 - 2			3.986 - 2			8.348 - 3
Mo^{101}	4.051 - 1	5.635			8.005			1.118 - 1	8.398 - 6	0	0			0
Mo^{102}	1.164 + 1	1.103 + 1			6.410	1.920	3.148 - 1	2.826 - 2	1.647 - 7	0	0			0
Mo^{104}	2.218 + 1	1.728 + 1			1.424	5.560 - 3	1.356 - 6	0			0			0
Tc^{99m}	3.970 - 6	7.538 - 5			7.820 - 4			7.157 - 3			3.151 - 2			7.982 - 3
Tc^{99}	0	0			0			0			0			0
Tc^{101}	6.690 - 4	1.460 - 1			3.307			4.935 - 1	9.306 - 5	0	0			0
Tc^{102}	3.741	1.110 + 1			6.457	1.934	3.172 - 1	2.846 - 2	1.657 - 7	0	0			0
Tc^{104}	4.285 - 2	7.095 - 1			2.242	1.144	3.605 - 1	7.725 - 2	3.491 - 5	3.354 - 10	0			0
Tc^{105}	3.111	2.903			1.451	3.111	3.085 - 2	1.417 - 3	2.894 - 10	0	0			0
Ru^{103}	3.268 - 3	3.268 - 3			3.268 - 3			3.264 - 3			3.229 - 3			2.895 - 3

TABLE IV-9, cont'd.

ISOTOPE	0.1	1	3	6	10	30	60	100	300	600	1000	3000	6000	10,000
Ru^{105}	4.043 - 4	7.418 - 3			5.553 - 2			3.399 - 2			8.124 - 3	4.518 - 5	1.874 - 8	0
Ru^{106}	2.234 - 5	2.234 - 5			2.234 - 5			2.234 - 5			2.231 - 5			2.205 - 5
Ru^{107}	1.280	1.118			2.880	1.414 - 2	1.538 - 4	3.707 - 7	0		0			0
Rh^{103m}	9.907 - 1	1.872 - 5			1.857 - 4			1.146 - 3			1.612 - 3			1.445 - 3
Rh^{105m}	1.435 - 5	2.836 - 3			5.195 - 2			8.419 - 2			8.144 - 3	4.529 - 5	1.878 - 8	0
Rh^{105}	3.569 - 10	3.148 - 7	5.991 - 6		3.509 - 5	5.704 - 4		2.561 - 3			9.571 - 3			6.025 - 4
Rh^{106}	1.528 - 6	1.662 - 5			2.234 - 5			2.234 - 5			2.231 - 5			2.205 - 5
Rh^{107}	2.020 - 3	3.543 - 2			1.731 - 1			1.462 - 2	2.680 - 5	2.102 - 9	0			0
Pd^{107}	0	0			0			0			0			0
Pd^{109}	1.165 - 3	1.164 - 3			1.155 - 3			1.069 - 3			4.921 - 4	8.774 - 5	6.607 - 6	2.101 - 7
Pd^{111m}	1.793 - 4	1.789 - 4			1.756 - 4			1.453 - 4			2.196 - 5	3.293 - 7	6.046 - 10	0
Pd^{111}	2.549 - 2	2.481 - 2			1.895 - 2			1.365 - 3	7.993 - 5		1.769 - 5	2.652 - 7	4.870 - 10	0
Pd^{112}	2.478 - 4	2.477 - 4			2.465 - 4			2.346 - 4			1.430 - 4	4.758 - 5		1.012 - 5
Ag^{109m}	5.996 - 5	7.414 - 4			1.156 - 3			1.070 - 3			4.925 - 4	8.781 - 5	6.612 - 6	2.102 - 7
Ag^{111}	6.091 - 8	1.517 - 6			1.392 - 5			5.104 - 5			5.150 - 5			2.928 - 5
Ag^{112}	4.473 - 8	8.483 - 7			8.720 - 6			7.292 - 5			1.608 - 4	5.613 - 5		1.194 - 6
Ag^{115}	1.143 - 2	1.110 - 2			8.246 - 3			4.226 - 4	5.738 - 7	0	0			0
Cd^{115m}	5.818 - 10	1.090 - 8			9.879 - 8			3.396 - 7			3.491 - 7			3.156 - 7
Cd^{115}	2.663 - 5	2.864 - 5			4.569 - 5			9.111 - 5			7.698 - 5			1.082 - 5
Cd^{117m}	1.908 - 3	1.902 - 3			1.837 - 3			1.299 - 3	6.012 - 4		4.058 - 5	1.834 - 8	0	0
Cd^{117}	7.931 - 7	1.495 - 5			1.447 - 4			6.823 - 4			3.371 - 5	1.524 - 8	0	0
In^{115m}	3.409 - 9	6.446 - 8			6.667 - 7			5.923 - 6			2.107 - 5			3.276 - 6
In^{115}	0	0			0			0			0			0
In^{117m}	5.538 - 8	1.084 - 6			1.466 - 5			2.824 - 4			9.329 - 5	5.103 - 8	0	0
In^{117}	2.834 - 7	5.351 - 6			5.269 - 5			2.894 - 4			1.988 - 5	9.003 - 9	0	0
Sn^{117m}	0	0			0			0			0			0
Sn^{121}	2.839 - 4	2.838 - 4			2.827 - 4			2.722 - 4			1.865 - 4	3.051 - 5		4.253 - 6
Sn^{123}	2.073 - 7	2.073 - 7			2.073 - 7			2.072 - 7			2.065 - 7			2.001 - 7
Sn^{125}	2.623 - 2	2.456 - 2			1.275 - 2	2.987 - 3	3.607 - 4	4.712 - 5			2.793 - 5			1.779 - 5
Sn^{127}	3.559 - 2	3.540 - 2			3.351 - 2			1.939 - 2	5.747 - 3	9.275 - 4	8.149 - 5	4.267 - 10	0	0
Sn^{128}	2.026 - 1	2.004 - 1			1.817 - 1			6.014 - 2	5.284 - 3	1.376 - 4	1.062 - 6	0		0
Sn^{130}	2.370 + 1	1.865 + 1			1.693	8.183 - 3	2.751 - 6	0			0			0

TABLE IV-9, cont'd.

ISOTOPE	0.1	1	3	6	10	30	60	100	300	600	1000	3000	6000	10,000
Sn^{132}	6.568 + 1	4.946 + 1			2.902	5.318 - 3	4.172 - 7	0			0			0
Te^{125*}	0	0			0			0			0			0
Te^{127*}	1.321 - 6	1.321 - 6			1.321 - 6			1.321 - 6			1.315 - 6			1.262 - 6
Te^{127*}	0	0			0			0			0			0
Te^{129*}	5.682 - 5	5.715 - 5			6.045 - 5			8.962 - 5			1.911 - 4			1.808 - 4
Te^{129}	2.452 - 5	4.634 - 4			4.597 - 3			2.731 - 2			5.644 - 3	9.156 - 5		4.994 - 5
Te^{131*}	8.777 - 4	1.058 - 3			2.614 - 3			7.094 - 3			5.254 - 3			1.642 - 4
Te^{131}	4.325 - 3	8.006 - 2			6.430 - 1			4.552 - 1	5.136 - 3		1.065 - 3	4.930 - 4	1.553 - 4	3.738 - 6
Te^{132}	5.396 - 6	1.2192 - 3			2.634 - 2			3.132 - 2			2.736 - 2			7.094 - 3
Te^{133*}	2.941	2.906			2.577			7.764 - 1	5.398 - 2	9.898 - 4	4.785 - 6	0		0
Te^{134}	5.007	4.935			5.007			1.000	3.982 - 2	3.161 - 4	5.006 - 7	0		0
Sb^{125}	8.652 - 10	4.771 - 9			3.677 - 8			2.373 - 7			2.373 - 7			2.359 - 7
Sb^{126*}	0	1.590 - 8			1.226 - 7	0		0			0			0
Sb^{126}	0	0			0			0			0			0
Sb^{127}	2.260 - 7	4.283 - 6			4.344 - 5			3.363 - 4			6.672 - 4			2.133 - 4
Sb^{128}	2.727 - 3	1.418 - 2			9.192 - 2			7.314 - 2	8.148 - 3		8.377 - 4	7.914 - 5	2.303 - 6	2.061 - 8
Sb^{129}	7.952 - 2	7.934 - 2			7.757 - 2			6.188 - 2			6.458 - 3	4.256 - 5	2.278 - 8	0
Sb^{130}	1.158 - 1	1.876			4.276	7.409 - 1	3.986 - 2	8.026 - 4	0		0			0
Sb^{131}	3.525	3.431			2.616			1.736 - 1	4.184 - 4	4.951 - 8	0			0
Sb^{132}	1.078	1.540 + 1			8.854	4.235 - 2	5.446 - 6	0			0			0
I^{129}	0	0			0			0			0			0
I^{131}	1.222 - 8	2.337 - 6	2.141 - 5		2.598 - 4			5.763 - 3			5.631 - 3			3.355 - 3
I^{132}	1.799 - 9	2.043 - 6	4.495 - 5		6.905 - 4	3.558 - 3		1.183 - 2			2.798 - 2			7.312 - 3
I^{133}	5.013 - 2	5.156 - 2			6.496 - 2			1.346 - 1			1.021 - 1	3.363 - 2	6.355 - 3	6.891 - 4
I^{134}	5.582 - 1	5.905 - 1			1.038			1.676	2.624 - 1	7.004 - 3	4.068 - 5	0		0
I^{135}	4.737 - 1	4.730 - 1			4.657 - 1			3.988 - 1			8.451 - 2	2.688 - 3	1.525 - 5	1.543 - 8
I^{136}	6.594 + 1	4.267 + 1	1.622 + 1	3.802	5.494 - 1	3.462 - 5	0	0			0			0
I^{137}	4.235 + 2	9.138 + 1	3.025	1.822 - 2	1.998 - 5	0		0			0			0
Xe^{133*}	1.260 - 8	2.387 - 7			2.492 - 6			2.418 - 5			1.724 - 4			8.676 - 5
Xe^{133}	2.235 - 7	4.303 - 6			5.114 - 5			9.092 - 4	3.500 - 3		1.080 - 2			1.324 - 2
Xe^{135*}	4.076 - 1	3.970 - 1			3.112 - 1			1.272 - 1			2.636 - 2	8.384 - 4	4.756 - 6	4.812 - 9
Xe^{135}	4.642 - 5	8.752 - 4			8.506 - 3			5.833 - 2			1.391 - 1	2.259 - 2	6.491 - 4	4.500 - 6

TABLE IV-9, cont'd.

ISOTOPE	0.1	1	3	6	10	30	60	100	300	600	1000	3000	6000	10,000
Xe^{137}	3.847	3.466 1			9.152	2.618 - 1	1.037 - 6	0			0			0
Xe^{138}	1.006 1	9.701			6.722			1.714 - 1	4928 - 5	2.403 -10	0			0
Xe^{139}	2.346 2	9.419 1	1.239 1	5.917 - 1	1.025 - 2	0		0			0			0
Cs^{135}	0	0			0			0			0			0
Cs^{137}	3.026 - 7	1.248 - 6			9.910 - 6			1.217 - 5			1.217 - 5			1.119 - 9
Cs^{138}	2.53 - 1	4.378 - 1			1.783			1.148	1.802 - 2	2.831 - 5	5.150 - 0	0		0
Cs^{139}	4.373	1.382 1			1.096 1	2.547	2.853 - 1	1.541 - 2			0			0
Ba^{137*}	0	0			0			0			0			0
Ba^{139}	3.180 - 2	1.058 - 1			1.159 - 1			1.212	2.286 - 1	1.866 - 2	6.611 - 4	0		0
Ba^{140}	1.076 - 2	1.076 - 2			1.075 - 2			1.072 - 2			1.036 - 2			7.336 - 3
Ba^{141}	1.091 1	1.054 1			7.451			2.328 - 1	1.052 - 4	1.011 - 9	0			0
Ba^{142}	1.870 1	1.757 1			9.417	2.354	2.942 - 1	1.838 - 2	1.751 - 8	0	0			0
La^{140}	1.546 - 7	2.937 - 6			3.071 - 5			3.040 - 4			2.635 - 3			7.799 - 3
La^{141}	1.535 - 2	4.461 - 2			2.836 - 1			6.815 - 1			4.548 - 2	1.041 - 4	1.139 - 8	0
La^{142}	3.010 - 3	1.470 - 1			1.101			1.121	2.030 - 1	1.558 - 2	5.032 - 4	0		0
La^{143}	1.039 1	1.004 1			7.096			2.217 - 1	1.002 - 4	9.627 -10	0			0
Ce^{141}	1.089 0 8	4.058 - 7	2.613 - 6		2.294 - 5			8.474 - 4			3.948 - 3			3.655 - 3
Ce^{143}	1.820 - 4	3.359 - 3			3.077 - 2			9.019 - 2			6.730 - 2			2.771 - 3
Ce^{144}	4.647 - 4	4.647 - 4			4.647 - 4			4.646 - 4			4.639 - 4			4.568 - 4
Ce^{145}	4.095 1	3.326 1			4.159	4.098 - 2	4.008 - 5	3.891 - 9	0		0			0
Ce^{146}	6.881	6.579			4.200	1.549	3.470 - 1	4.720 - 2	2.199 - 6	0	0			0
Ce^{148}	7.610 1	2.984 1	3.728	1.646 - 1	2.570 - 3	0		0			0			0
Pr^{143}	4.750 - 5	4.755 - 5			5.307 - 5			2.913 - 4			2.741 - 3			7.149 - 3
Pr^{144}	9.244 - 7	1.726 - 5			1.521 - 4			4.560 - 4			4.639 - 4			4.568 - 4
Pr^{145}	8.983 - 3	6.840 - 2			3.086 - 1			2.877 - 1			5.047 - 2	1.046 - 3	3.124 - 6	1.343 - 9
Pr^{146}	9.773 - 1	1.794 - 1			1.323			4.713 - 1	1.815 - 3	3.616 - 7	0			0
Pr^{147}	7.006	6.651			3.955	1.246	2.202 - 1	2.185 - 2	2.101 - 7	0	0			0
Pr^{148}	1.360	1.419 1			1.209	9.890 - 4	2.309 - 8	0			0			0
Nd^{144}	0	0			0			0			0			0
Nd^{147}	1.520 - 5	2.816 - 4			2.305 - 3			5.239 - 3			5.054 - 3			3.421 -3
Nd^{149}	2.940 - 1	2.924 - 1			2.776 - 1			1.651 - 1	6.200 - 2	9.193 - 3	9.122 - 4	8.772 - 9	0	0
Nd^{151}	1.054	1.005			6.218 - 1	2.141 - 1	4.324 - 2	5.124 - 3	1.197 - 7	0	0			0

TABLE IV-9, cont'd.

ISOTOPE	.1	1	3	6	10	30	60	100	300	600	1000	3000	5000	10,000
Pm^{147}	0	0			0			0			0			0
Pm^{149}	3.199 - 6	6.062 - 5			6.180 - 4			4.801 - 3			9.225 - 3			1.306 - 3
Pm^{151}	2.146 - 5	3.982 - 4			3.313 - 3			7.763 - 3			5.410 - 3			1.390 - 4
Sm^{147}	0	0			0			0			0			0
Sm^{151}	0	0			0			0			0			0
Sm^{153}	1.661 - 3	1.661 - 3			1.657 - 3			1.621 - 3			1.299 - 3			1.422 - 4
Sm^{155}	4.288 - 2	4.178 - 2			3.221 - 2			2.394 - 3	7.426 - 6	1.222 - 9	0			0
Sm^{156}	7.520 - 4	7.511 - 4			7.425 - 4			6.615 - 4			2.083 - 4	1.597 - 5	3.392 - 7	1.995 - 9
Eu^{155}	7.067 - 10	1.326 - 8			1.224 - 7			4.626 - 7			4.897 - 7			4.823 - 7
Eu^{156}	1.410 - 6	1.431 - 6			1.640 - 6			3.506 - 6			1.436 - 5			1.476 - 5
Eu^{157}	2.636 - 4	2.634 - 4			2.617 - 4			2.446 - 4			1.245 - 4	2.777 - 5	2.925 - 5	1.455 - 7
Eu^{158}	1.040 - 3	1.029 - 3			9.278 - 4			3.281 - 4	3.257 - 5	1.018 - 5	1.005 - 5	0		0
Gd^{159}	3.094 - 5	3.092 - 5			3.074 - 5			2.902 - 5			1.625 - 5	4.512 - 5	6.579 - 7	5.049 - 3
Gd^{161}	6.354 - 4	5.368 - 4			9.943 - 5	2.349 - 6	5.522 - 9	0			0			0
Tb^{161}	2.223 - 9	3.893 - 8			2.017 - 7			2.375 - 7			2.223 - 7			1.189 - 7
Sn^{126}	0	0			0			0			0			0

TABLE IV-9, cont'd.

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been extracted and the gamma power for this group of elements has been calculated, using the decay scheme energy data tabulated in ORNL-2127.[95] The elements have been divided into three groups: noble gases, halogens (plus tellurium), and the remainder. This information is presented graphically in Figure IV-10 by group. From this figure it can be noted that the most important is the halogen-tellurium group, particularly after about sixteen hours when this group contributes essentially all of the gamma power. Some uncertainty exists with respect to the shape of the curve between ten and one hundred minutes, since the fission product inventory provided does not include sufficient data to determine intermediate points in this region. However, this is not felt to create a significant difficulty for preliminary evaluations of hazard.

Figure IV-11 indicates the gamma power of those fission products released with the assumption of 20 percent core vaporization. The residual fission product gamma power indicated in this figure was obtained by comparing the volatile gamma power determined from WANL and ORNL data with a fission product inventory computation performed by the Martin Company[96] and using the difference to obtain an indication of the residual fission product gamma power. Again, it will be noted that the volatile elements contribute by far the major portion of the gamma power for the release being considered at times of one hour and more. Therefore, any errors inherent in the use of fission product inventories from two sources for the computation of the gamma power in this case should not be too significant.

d. Spatial Distribution

For the purposes of this analysis, it is assumed that the excursion results in an instantaneous puff release comprising a point source at the ground level. This assumption is conservative, although in fact a modest cloud rise does not create any special advantage except at close-in distances, at which other radiation doses (i.e., the prompt gamma and neutron dose) would be much more significant than those from the passing cloud. In the event that this accident occurs within a building, the treatment afforded herein will not apply in any case.

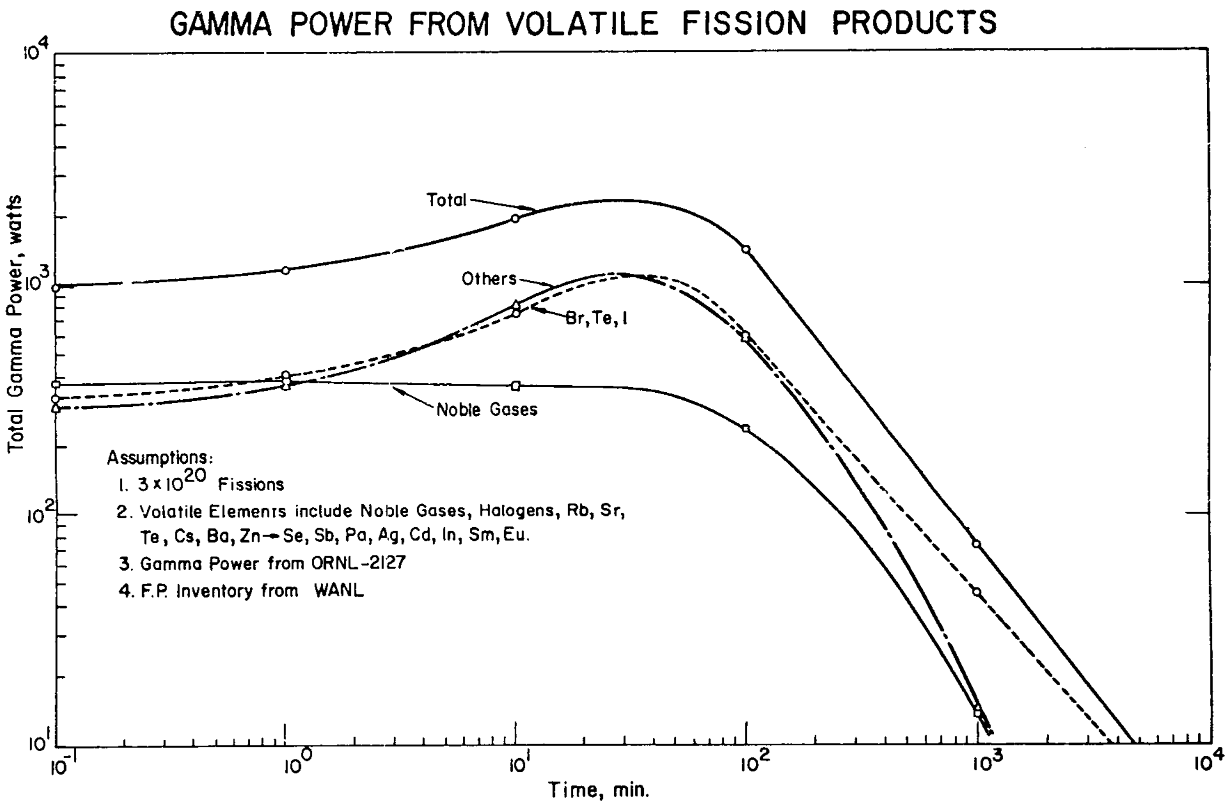
GAMMA POWER FROM VOLATILE FISSION PRODUCTS
Total Gamma Power, watts
Time, min.
Total
Others
Br, Te, I
Noble Gases
Assumptions:
1. 3 x 10^20 Fissions
2. Volatile Elements include Noble Gases, Halogens, Rb, Sr, Te, Cs, Ba, Zn→Se, Sb, Pa, Ag, Cd, In, Sm, Eu.
3. Gamma Power from ORNL-2127
4. F.P. Inventory from WANL

Figure IV-10

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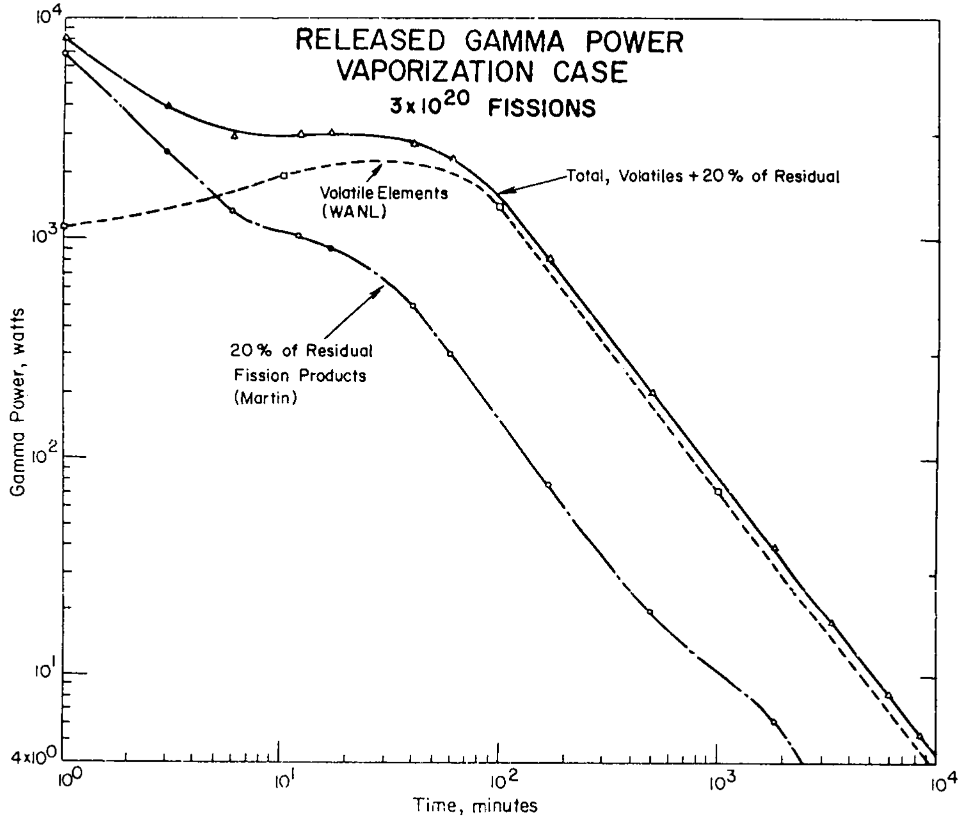

Figure IV-11

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3. Dose-Distance Relationships

For this accident ($\sim 10^4$ MW-sec) several contributions to dose are considered for the various meteorological conditions selected previously. These doses include the prompt neutron and gamma doses from the excursion itself; the whole body gamma dose delivered during passage of the cloud downwind; the dose to thyroid from inhalation of iodine; the gamma dose from deposition of material in the dry state on a surface; and the ingestion doses resulting from contamination of land surfaces and water under dry and rainy conditions.

a. External Dose

External dose may result from the prompt radiation accompanying the excursion; from the passage of the cloud; and from surface contamination deposited by the cloud during its passage Prompt radiation doses were determined from data presented in The Effects of Nuclear Weapons[97] and are shown in Figure IV-12. The assumption is made in this reference that the relative biological effectiveness for the whole body dose from neutrons is one. With this assumption, it can be noted that the neutrons provide the most significant fraction of the total (neutron plus gamma) dose out to a distance of some 800 meters. Should the RBE not be equal to one but higher, say two or more, this importance would extend out to considerably greater ranges. From this figure, it may be noted that, with the assumptions made, lethal doses would be delivered within about 200 meters, neglecting attenuation of the radiation by self-shielding or external shielding by materials surrounding the core. The occurrence of an excursion of this magnitude within a building in an unshielded area would undoubtedly result in a high degree of injury to surrounding workers.

The second source of whole body gamma dose is due to the passage of the fission product cloud downwind from the excursion. Whole body gamma doses to individuals on the centerline are indicated in Figure IV-13 for the release of volatile elements, and in Figure IV-14 for the 20 percent vaporization case.

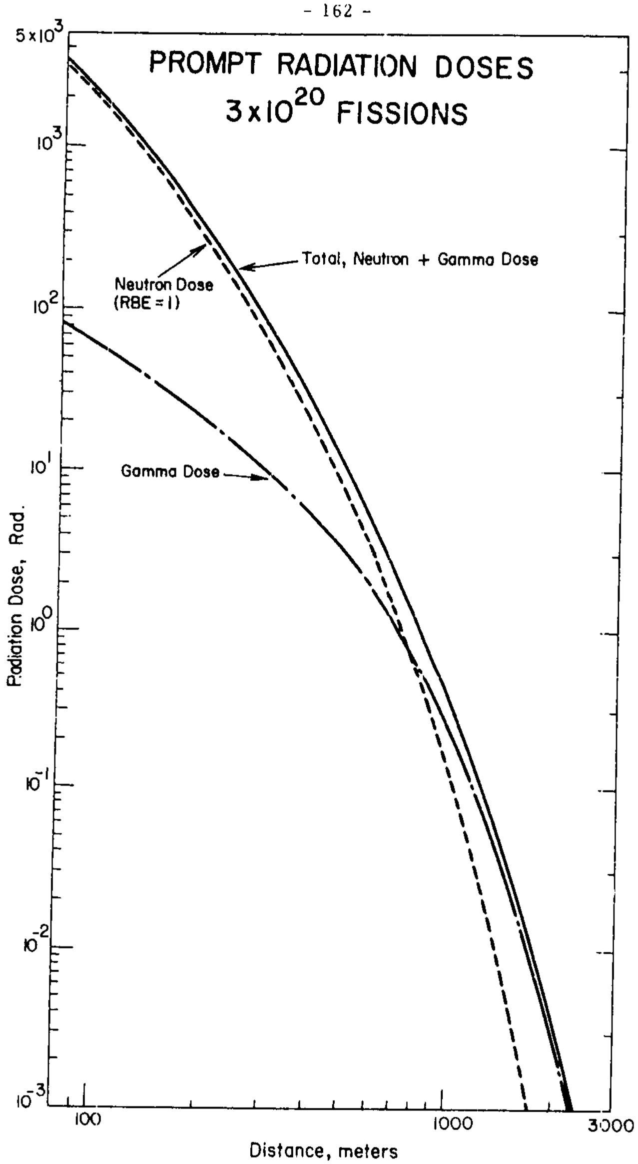
PROMPT RADIATION DOSES
3x10^20 FISSIONS
Neutron Dose
(RBE = 1)
Total, Neutron + Gamma Dose
Gamma Dose
Radiation Dose, Rad.
Distance, meters
5x10^3
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
100
1000
3000

Figure IV-12

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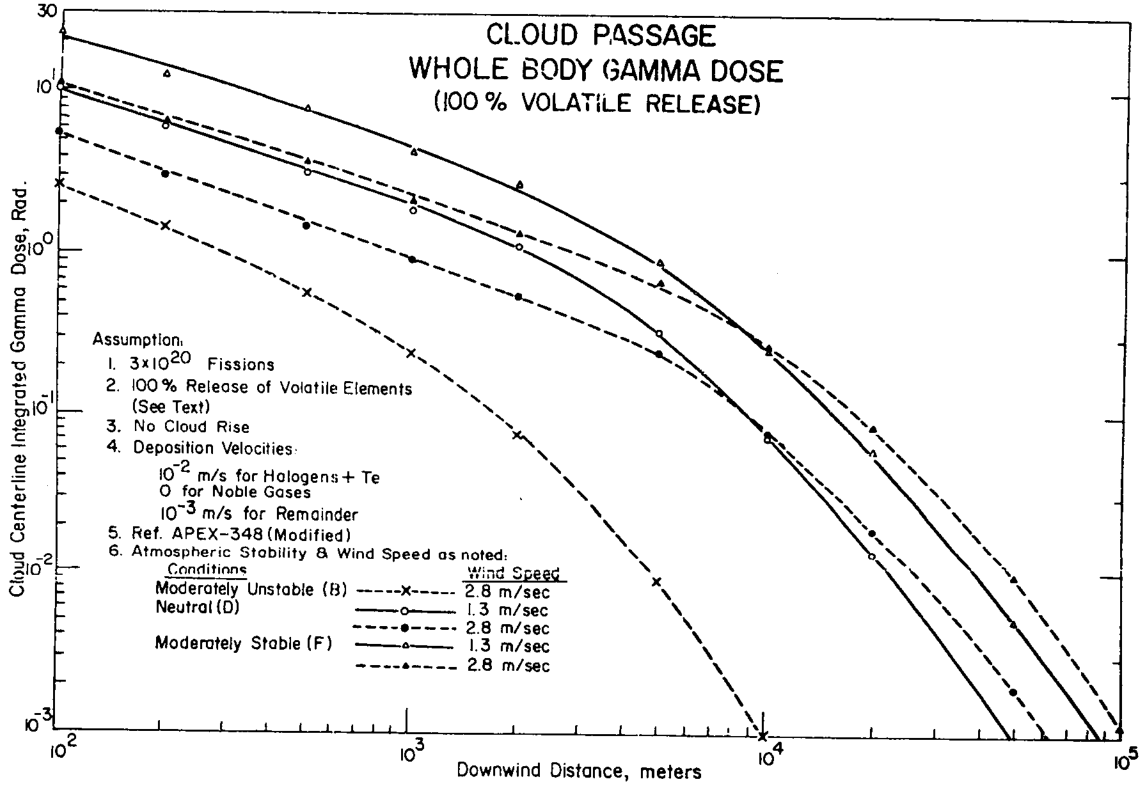

Figure IV-13

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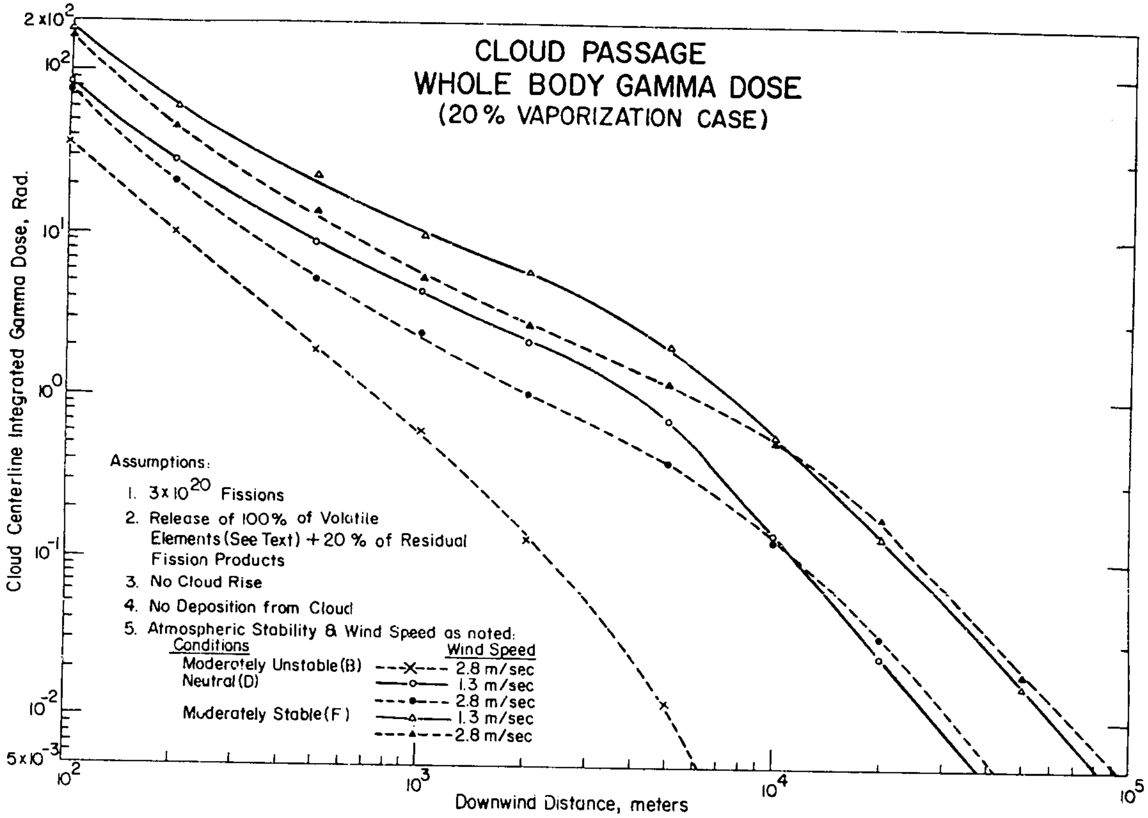

Figure IV-14

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In Figure IV-13 for the volatile release, consideration is given to deposition of the materials which are not noble gases, as indicated in the preceding section, and results are shown for various conditions of atmospheric stability and wind speed. For the most extreme case, a moderately stable atmosphere with a wind speed of 1.3 meters per second, doses from cloud passage are less than 25 rad at distances as low as 100 meters from the release. Doses greater than 0.5 rad do not occur beyond distances of 7,000 meters (4.35 miles), even under the most restrictive meteorological conditions treated in this analysis.

Figure IV-14 indicates the whole body gamma dose from cloud passage for the 20 percent vaporization case. This is felt to be a most conservative approach since in addition to the release of the 20 percent residual source term no cloud depletion during passage of the cloud is considered to occur. However, even with the conservative assumptions employed in this treatment under the most restrictive meteorological conditions examined, a dose of 25 rad during cloud passage would not be delivered at distances greater than about 500 meters (approximately 0.3 miles). Using the unrealistic assumption that there will be no ground deposition, the distance required to produce an integrated dose during cloud passage of 0.5 rad would be approximately 11,000 meters (approximately 7 miles).

Surface contamination dose rates from material deposited by the passing cloud with the assumed deposition velocities are indicated in Figure IV-15. As indicated in the preceding section, the model employed for this computation, although providing a more indicative representation than one based on uniform contamination of an arbitrary area does possess shortcomings due to neglect of air scattering. Data are presented in this figure for the dose rate as a function of time for distances ranging from 150 meters to 15,000 meters downwind under conditions producing the greatest deposition; that is, inversion and neutral conditions for low wind speeds (1.3 meters per second). It is possible to integrate under these curves by a combination of numerical and analytical

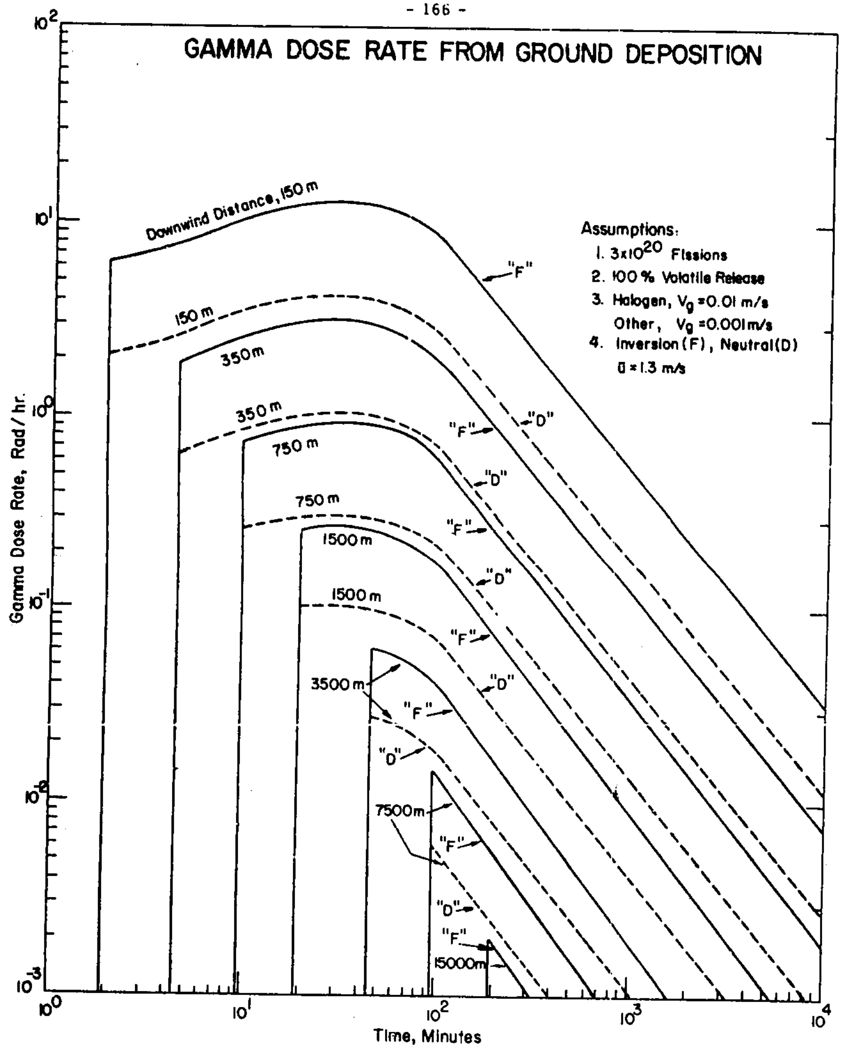

Figure IV-15

techniques to obtain the integral dose to which an individual would be exposed on remaining indefinitely at the distances indicated. These integral dose values are tabulated in Table IV-10 for the inversion case which is the most restrictive.

TABLE IV-10

INTEGRATED GAMMA DOSE FOR INFINITE EXPOSURE TO SURFACE CONTAMINATION

(Atmosphere: Moderately Stable; Wind Speed: 1.3 meters per second)

Downwind Distance (Meters)	Infinite Dose (rads)
350	10
750	2.65
1,500	0.7
3,500	0.14
7,500	0.032
15,000	0.0039

From these data, it may be seen that the fallout dose from the postulated ground release is not severe even under the restrictive conditions noted, except at distances quite close to the source. In this regard some provision must, therefore, be considered for decontamination of surfaces in the vicinity of handling or launch facilities, as well as to a consideration of the ion exchange capacity of soils to which contaminated liquids might be discharged during decontamination operations.

To provide an indication of the areal extent of integrated gamma dose delivered by cloud passage, Figures IV-16, IV-17, and IV-18 indicate the gamma dose isopleths for moderately unstable, neutral and moderately stable conditions. From these figures, it may be seen that with respect to both on-site and off-site individuals the cloud from accidents occurring

"NUCLEAR CRITICALITY ACCIDENT"
GAMMA DOSE ISOPLETHS
FROM CLOUD PASSAGE OF VOLATILE ELEMENTS
(3×10^{20} FISSIONS - MODERATELY UNSTABLE)

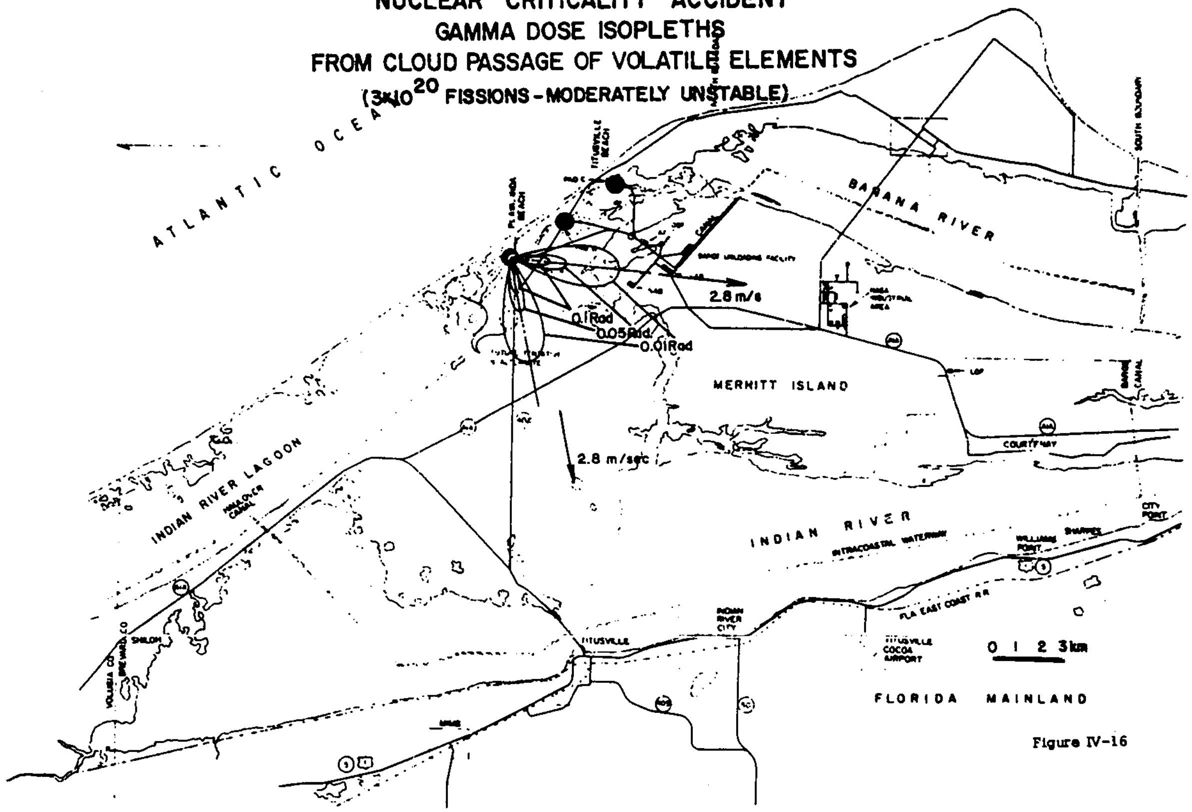

Figure IV-16

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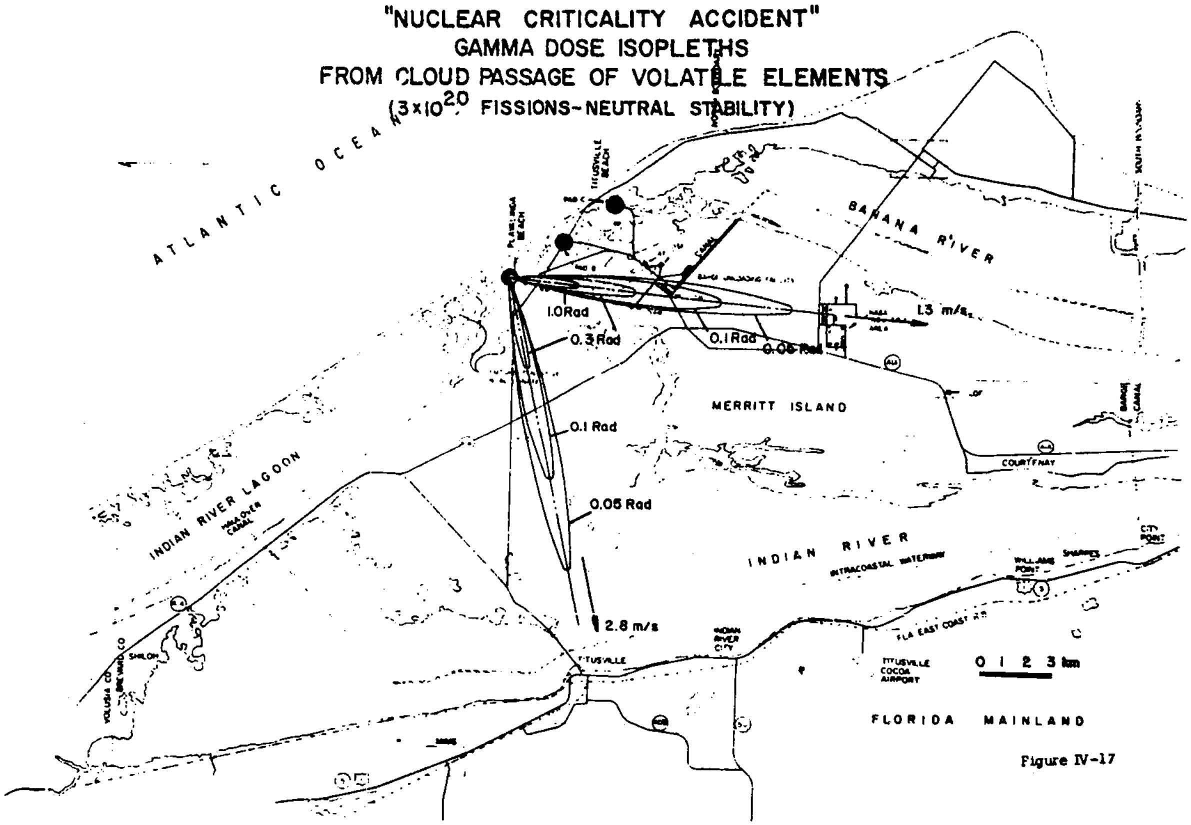

Figure IV-17

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"NUCLEAR CRITICALITY ACCIDENT"
GAMMA DOSE ISOPLETHS
FROM CLOUD PASSAGE OF VOLATILE ELEMENTS
(3×10^{20} FISSIONS-MODERATELY STABLE)

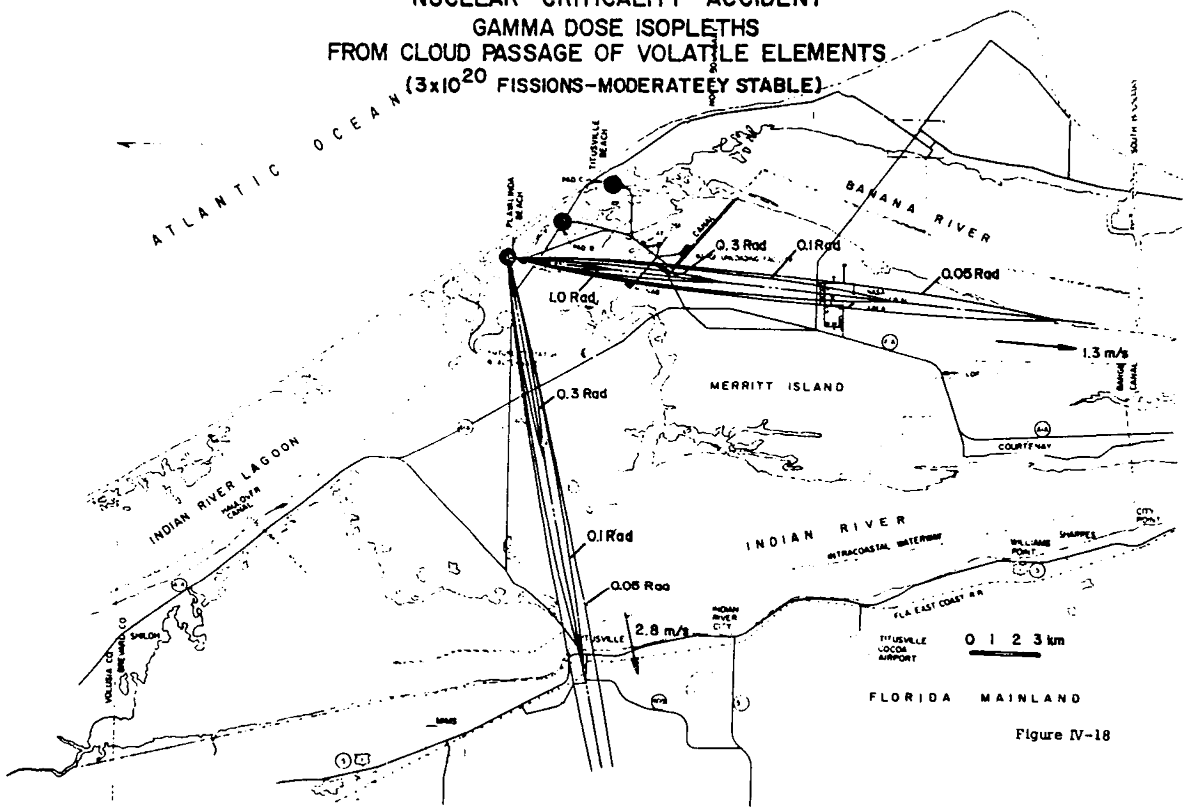

Figure IV-18

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in the vicinity of Pad A would not deliver doses which are excessive. Even under moderately stable conditions the doses at the vertical assembly building would be on the order of one to two rad; at the new NASA industrial area, approximately 0.3 rad; and at Titusville, about 0.1 rad. Under neutral stability or moderate lapse conditions, the doses to individuals would be lower. However, due to the increased width of cloud, the number of people affected to some extent might be greater, depending upon the particular trajectory.

b. Internal Dose

The internal doses considered for this accident are those deriving from the inhalation of material as it passes in the cloud and from ingestion of material via the water and food route.

(1) Inhalation Doses

The inhalation dose based upon radioiodine in the cloud is considered of prime importance. Using the model described previously, thyroid doses from iodine inhalation on the cloud centerline were computed for this accident assuming the deposition velocity of 1 centimeter per second indicated earlier. This deposition velocity was assumed to apply to the iodine precursors (not verified by experiment), as well as to iodine, and the assumption was made that these precursors were inhaled and retained as efficiently as iodine. The results of these computations are shown in Figure IV-19. It can be noted from this figure that the thyroid doses from iodine are extremely high at distances of a few hundred meters, but that they decrease rapidly, reaching a value of 300 rads at distances less than 1,000 meters under any atmospheric stability and wind speed conditions treated. It can also be noted that the doses from the inversion release decrease more rapidly than do those from the neutral condition due to the greater depletion of the cloud through deposition.

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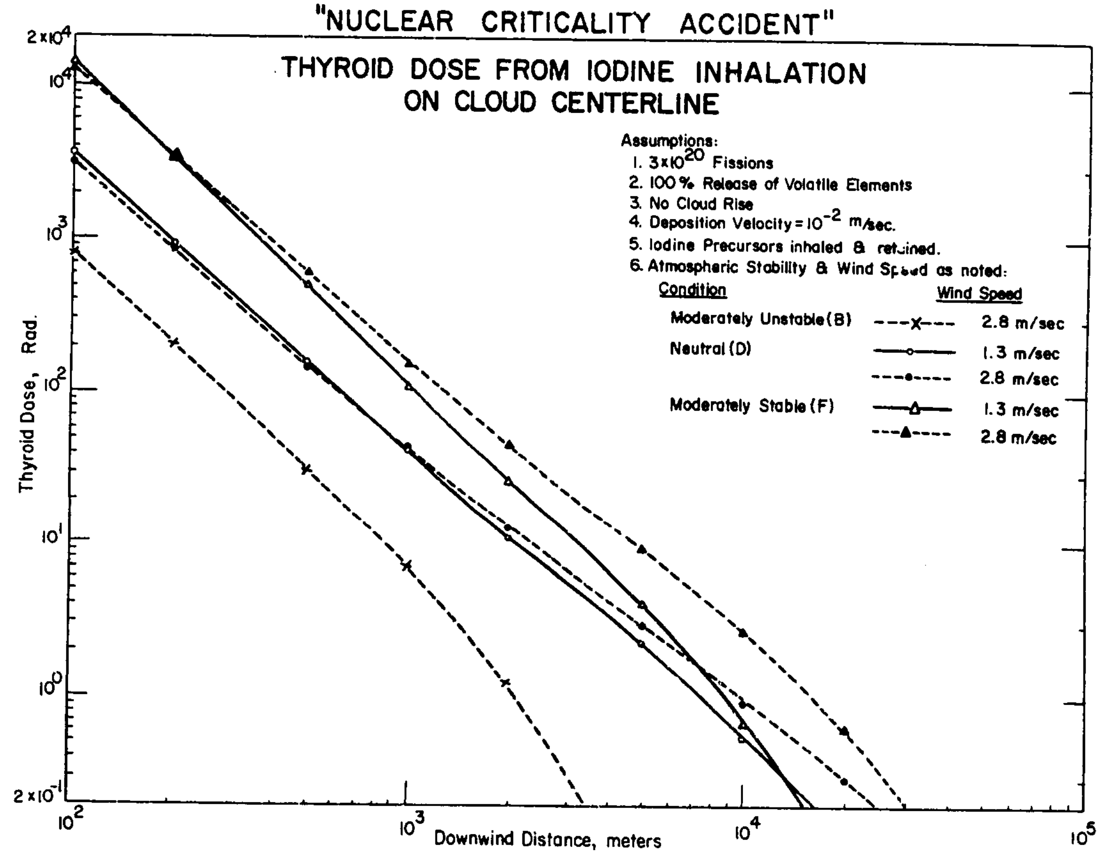

Figure IV-19

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The effect of the deposition velocity on the thyroid dose is shown for inversion and lapse conditions on Figure IV-20. In this figure thyroid doses are plotted for deposition velocities ranging from 0 to 1 centimeter per second. The significance of this parameter is indicated by the marked increase in thyroid dose, particularly at large distances. The difference in dose between deposition velocities of 0 and 1 centimeter per second exceeds an order of magnitude at distances of 2,000 meters and more. However, even assuming that no depletion of the cloud occurs, a dose of 300 rad to the thyroid is achieved at a distance of 2,000 meters, under the assumption of moderately stable conditions and a wind speed of 1.3 meters per second. Further reduction by an order of magnitude to a dose of 30 rads is achieved at a downwind distance of 10^4 meters. With a deposition velocity of 0.5 centimeter per second, these doses are reached at distances of 1,000 and 4,000 meters, respectively.

Another indication of the areal extent of thyroid doses is indicated in Figure IV-21 and IV-22, in which thyroid doses are indicated for neutral conditions and for moderately stable conditions, with deposition. From Figure IV-23, which indicates the thyroid dose isopleths with no iodine deposition, it may be seen that individuals in the Complex 39 assembly area would be subjected to a thyroid dose of between 30 and 100 rads from an accident originating at Pad A; and that unprotected workers in the NASA industrial area would be subject to a maximum of about 20 rads. With a westerly wind, a significant portion of the Titusville area would be exposed to doses on the order of 5 rad to the thyroid. With the assumption of a deposition velocity of 1 centimeter per second, the doses at the Complex 39 assembly area would be reduced to about 2 rads; at the new NASA industrial area to about 0.3 rad; and at Titusville to less than 1 rad.

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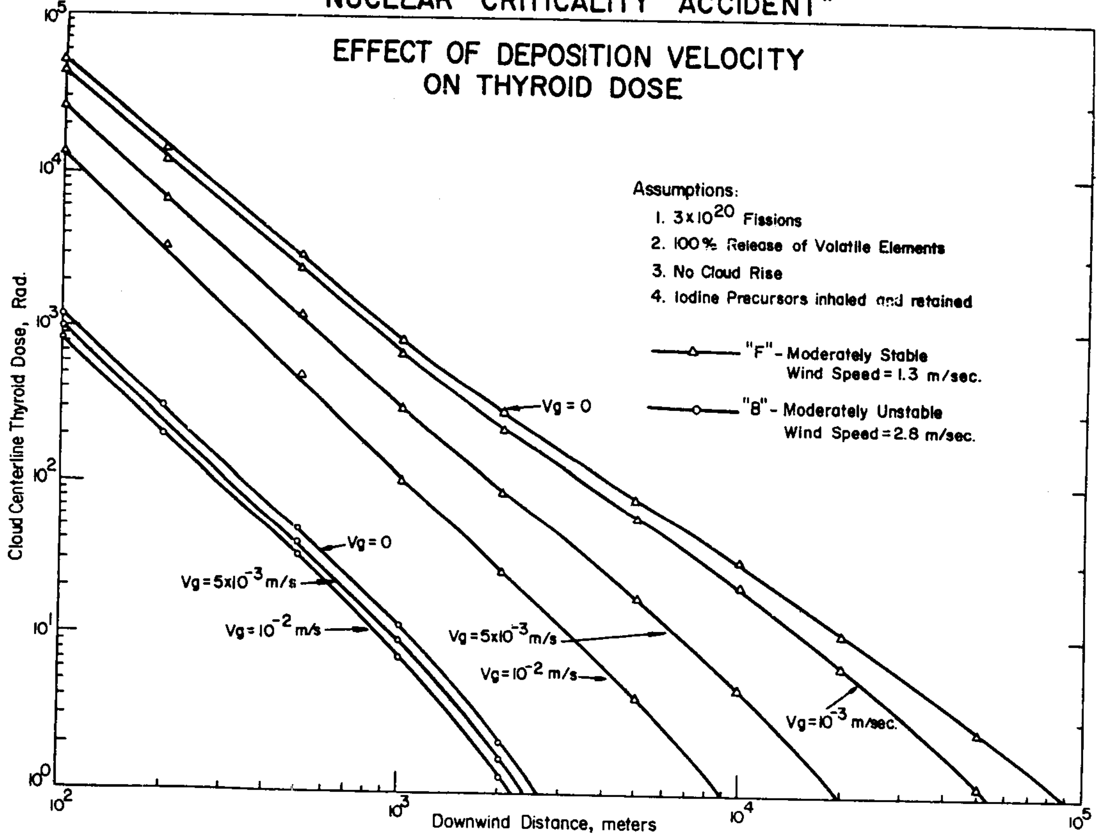

Figure IV-20

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"NUCLEAR CRITICALITY ACCIDENT"
THYROID DOSE ISOPLETHS
(NEUTRAL STABILITY)

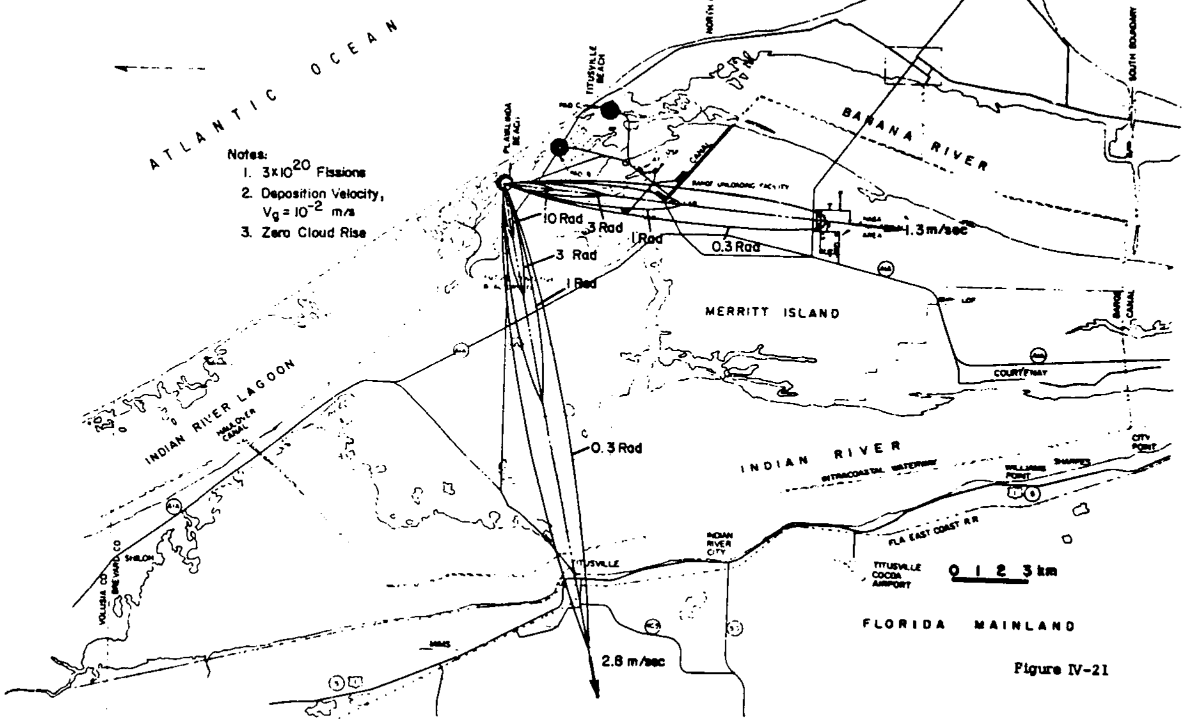

Figure IV-21

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"NUCLEAR CRITICALITY ACCIDENT"
THYROID DOSE ISOPLETHS
(MODERATE STABILITY)

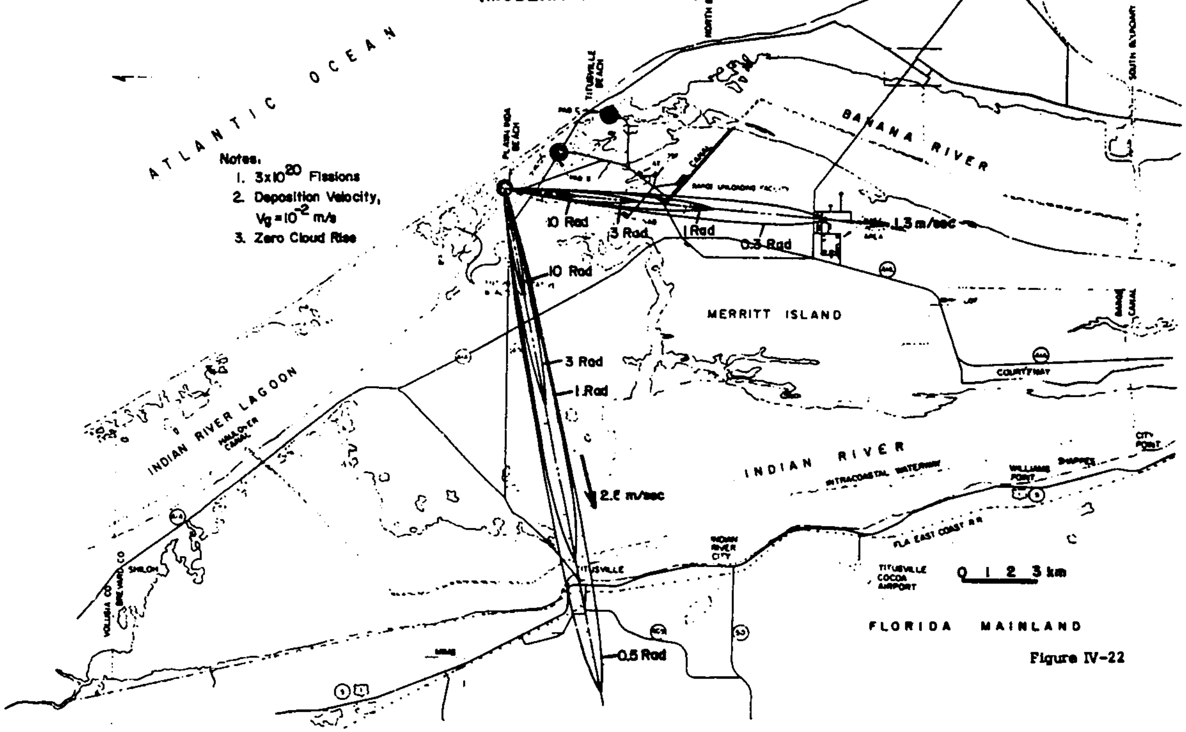

Figure IV-22

"NUCLEAR CRITICALITY ACCIDENT"
THYROID DOSE ISOPLETHS
(MODERATE STABILITY)

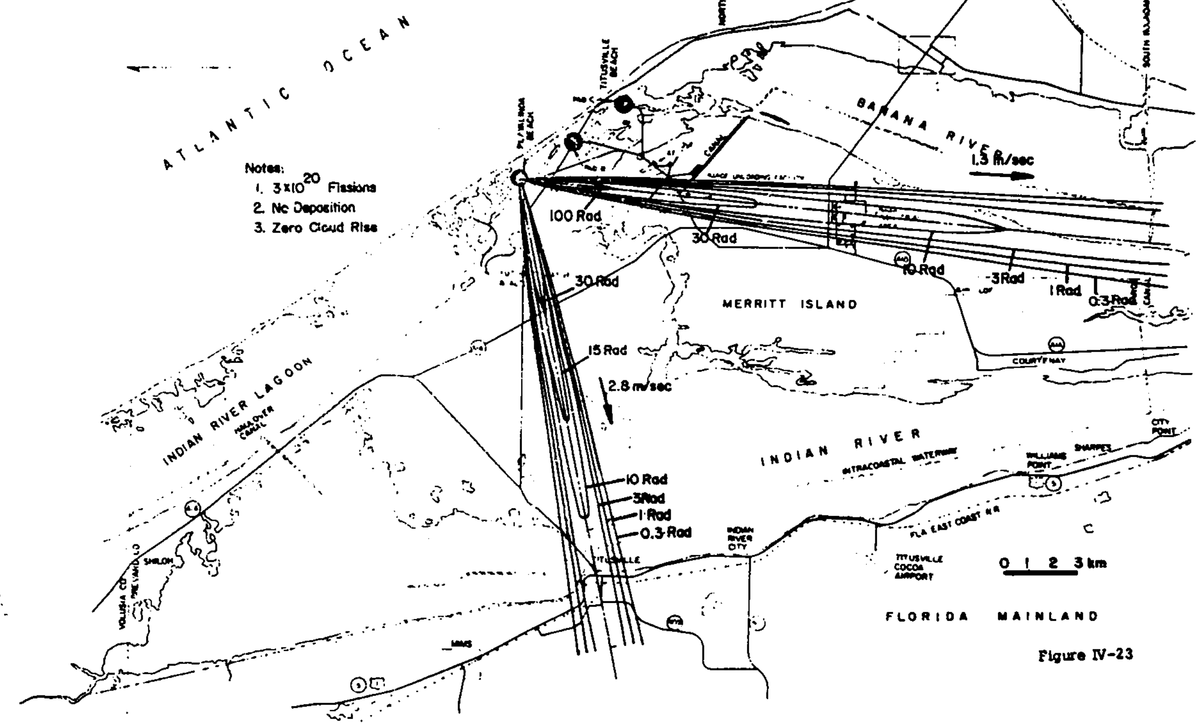

Figure IV-23

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(2) Ingestion Doses

Ingestion doses derive from the deposition of radioactive material on ground and water surfaces and their subsequent transmission to the population via the water or food chain. Since this becomes a problem only in off-site areas, deposition was computed for distances ranging from 10 to 100 kilometers for the neutral and inversion case.

As indicated in Figure IV-19, the wind speed of 2.8 meters per second which applies generally to westerly directed winds provides a higher concentration at large distances than does the lower wind speed due to the decrease in decay time and to the decrease in depletion from the cloud. Therefore, a wind speed of 2.8 meters per second was used to compute the deposition of Iodine-131, Strontium-89, Strontium-90, and Barium-140.

Deposition velocities of 10^{-3}, 2.5×10^{-3}, 5×10^{-3}, and 10^{-2} meters per second were used for Iodine-131 deposition in order to indicate the effect of this parameter on the surface contamination. The results of these computations are indicated in Figure IV-24. Since the deposition is the product of deposition velocity and time-integrated concentration at a point, and the time-integrated concentration is affected significantly by the deposition velocity in the model used, it will be seen from Figure IV-24 that deposition is maximimized by a deposition velocity of approximately 5×10^{-3} meters per second for close-in distances, and by a value of about 2.5×10^{-3} meters per second at distances greater than about 35,000 meters. For the bone seekers, strontium and barium, a deposition velocity of 10^{-3} meters per second was used and the results are shown in Figure IV-25.

Lake Washington, about 7 1/2 miles west of Eau Gallie, is in use as a drinking water supply for the City of Melbourne. This lake with a surface area of about 1.3×10^{7} square meters is located about 55 kilometers south-southwest of Pad A, and is presently the only substantial surface water supply in the area considered.

EFFECT OF DEPOSITION VELOCITY ON I^{131} DEPOSITION

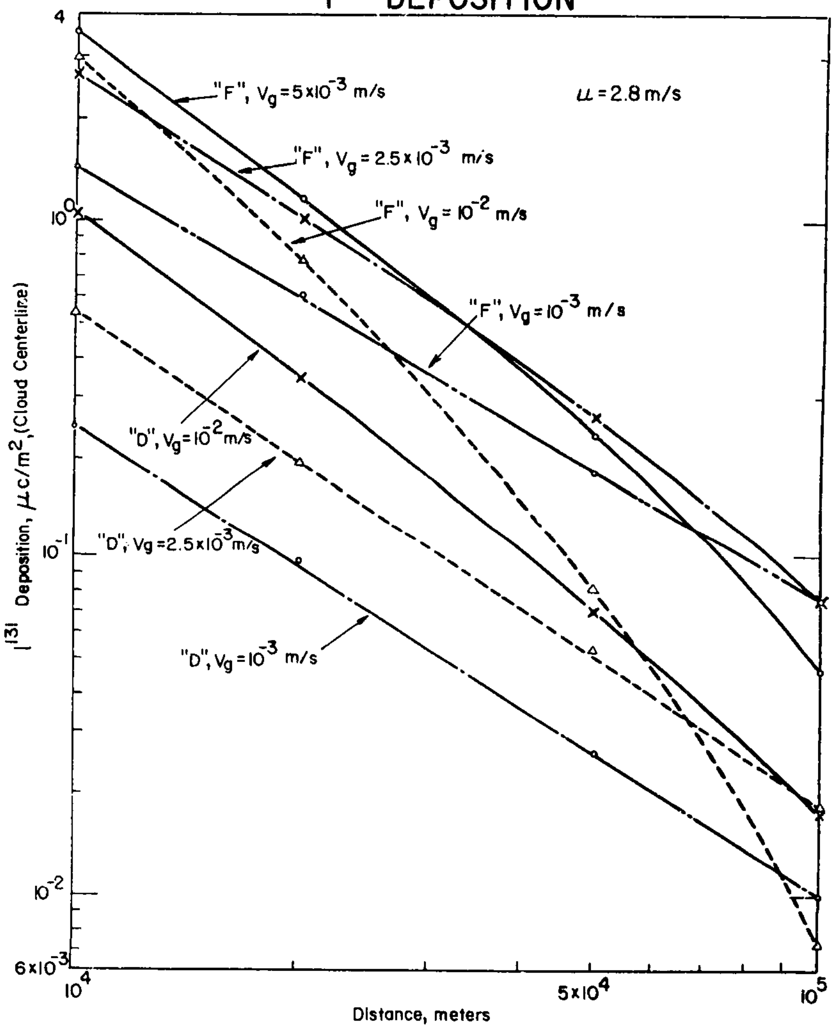


Figure IV-24

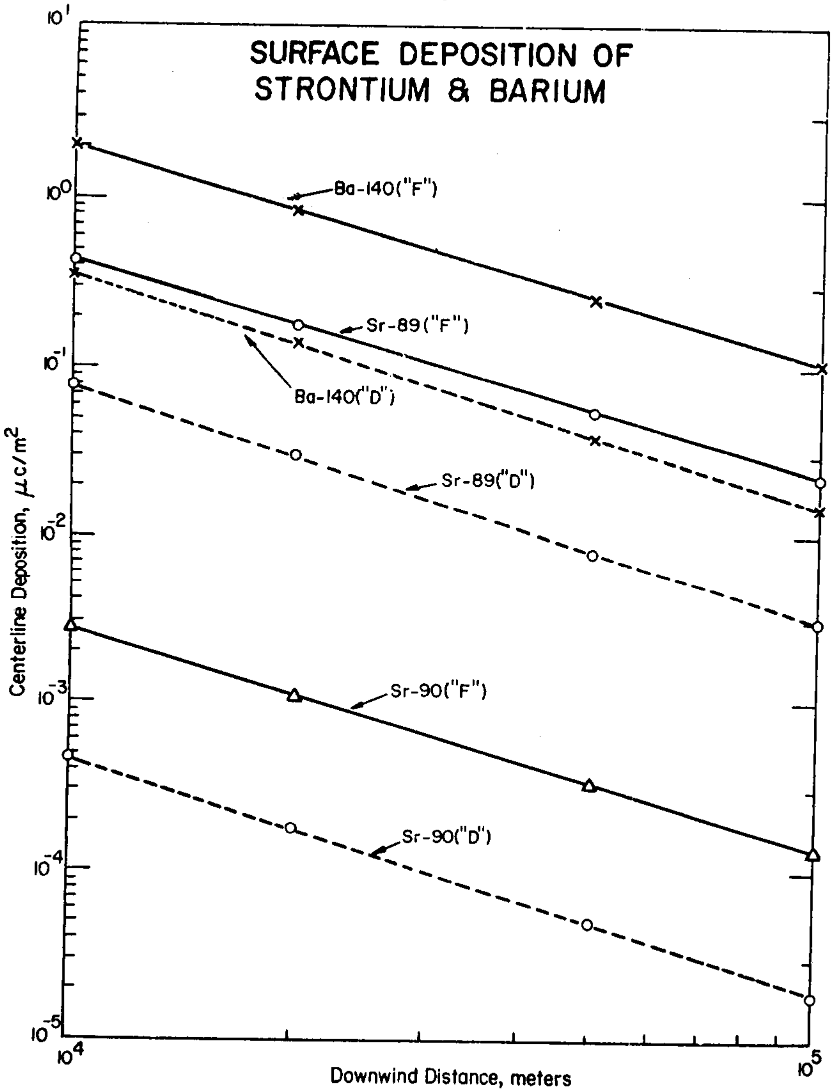


Figure IV-25

From Figure IV-24, it may be seen that deposition at a distance of 55 kilometers would be maximum with v_g equal to 2.5×10^{-3} meters per second. This maximum deposition would approximate 0.22 microcuries of Iodine-131 per square meter. If it is assumed that the iodine so deposited in the water of Lake Washington is mixed with only the top 10 centimeters, the concentration in the top layer of the water would be 2.2×10^{-6} microcuries per cubic centimeter. Using the previously derived acute (short time) ingestion limit of 0.08 microcuries for a child, this would require consumption of approximately 36 liters of water in the period of a few days to provide the acute exposure dose of 1.5 rem to the thyroid. For an adult, the acceptable intake limit and the volume of water required would both be increased by a factor of about 10. Therefore, the deposition of iodine in Lake Washington under these circumstances should create no significant hazard.

A similar analysis of Strontium-89 deposited under stable conditions 55 kilometers downwind from the source provides a value of 0.05 microcuries per square meter. Again, assuming mixing with the top 10 centimeters of the lake only, the Strontium-89 concentration would then be 5×10^{-7} microcuries per cubic centimeter. This is a factor of 20 less than the NCRP MPC_w for continuous non-occupational exposure (10^{-5} microcuries per cubic centimeter). For Strontium-90, a similar calculation yields a value of about 3×10^{-9} microcuries per cubic centimeter, which again is greater than a factor of 30 less than the continuous exposure MPC_w (10^{-7} microcuries per cubic centimeter).

A similar computation for Barium-140 indicates a concentration in the top 10 centimeters of water of approximately 2.4×10^{-6} microcuries per cubic centimeter, again less than the continuous non-occupational permissible concentration in water for this radionuclide (3×10^{-5} microcuries per cubic centimeter). Thus, it appears that deposition of radioactive materials in Lake Washington should not create a significant hazard, although in the event of an airborne release, contamination should be monitored at this spot.

A similar exercise for Lake Poinsett, 40 kilometers southwest of the site, indicates that iodine, strontium and barium deposition would be higher there than at Lake Washington by about a factor of two, producing concentrations which are still well below the acute intake levels derived earlier.

The approach to food contamination has been described in Section III-C. The critical food item is considered to be fresh milk and the most significant isotope is Iodine-131. With the assumptions made in Section III-C, it was indicated that, if deposition of this isotope should exceed 0.07 microcuries per square meter, the milk intake would need to be restricted following the accident. With the most pessimistic deposition velocity of 2.5×10^{-3} meters per second, as indicated in Figure IV-24, this value would be exceeded at all distances less than about 100,000 meters (approximately 60 miles). This distance would extend considerably beyond the limits of Brevard County into the counties of Oceola, Orange, Seminole and Volusia, although the cloud path under inversion conditions would tend to be rather narrow and not necessarily straight.

Using the data presented in ORO-545,[38] the area enclosed by a ground level concentration isopleth of a particular value can be estimated. Converting the deposition into an equivalent air concentration for each of the four deposition velocities treated in Figure IV-24, a contaminated area ranging between 10^7 and 10^8 square meters (about 2,500 to 25,000 acres) is derived. To facilitate control action in the event of an accident, it would appear in order to identify precisely those farms which produce milk either for home consumption or for sale and to maintain an up-to-date inventory of the location and extent of dairying industries in the surrounding counties.

For strontium and barium, somewhat more tenuous relationships between pasture contamination and milk concentration are established. As described in Section III-C, an approximation which can be derived from the Windscale data and information on fallout leads to an indication that 1 microcurie per square meter of pasture yields 0.01 microcurie of strontium per liter in milk. Again, assuming uncontrolled intake of strontium in milk leads to acceptable pasturage contamination values of 6.6 microcuries per square meter for Strontium-89, 0.02 microcurie per square meter for Strontium-90, and 490 microcuries per square meter for Barium-140. An examination of the deposition of strontium and barium indicated in Figure IV-25 indicates that these values are not exceeded at any point beyond the site limits under dry conditions.

The final mechanism for the deposition of material on the ground may occur as the result of rainfall stripping material from the cloud and depositing it upon the ground. Values for the depletion rate of material in a cloud from rain are open to discussion and vary with the size and intensity of the rainfall and the size and density of the particulates in the cloud. However, on an analytical basis, it is possible to determine the maximum surface deposition at any distance downwind. This relationship has been expressed by Gifford,[43] as

$$\frac{\omega_r\,(\max)_x}{Q} = \frac{1}{xe\,(2\pi)^{1/2}\,\sigma_y} \qquad \text{(IV-1)}$$

where $\omega_r\,(\max)_x$ is the maximum activity per unit area x meters downwind, and the other symbols are as defined in Section III.

Since by this relationship the deposition would be at a maximum when σ_y is a minimum, the inversion case again provides the limiting condition for rainout. Deposition from rainout over the range of 10,000 to 100,000 meters calculated from this expression for the inversion condition is indicated in Figure IV-26 for Iodine-131, Strontium-89, Strontium-90 and Barium-140.

From this figure it can be seen that the limits for pasture contamination indicated above are not reached by rainout at any point beyond the confines of the launch area, with the exception of Iodine-131. For this isotope the suggested limit of 0.07 microcuries per square meter could be expected at distances greater than 100,000 meters, or more than 60 miles from the launch site. However, in this case it should be recognized that the deposition does not take place continuously out to this distance, but rather that the values shown are the maximum deposition values which could occur at a given distance from the release. In the event of an accident which is followed by local squalls or thunderstorms in a direction downwind from the site of the accident, recognition must be given to the necessity for halting the consumption of milk at the earliest possible moment.

4. Dose Summary - Nuclear Criticality Accident

For an accident of the type hypothesized and the resulting doses, it is possible to state that an accident occurring at or near Pad A with a surface release of fission products would not create acute injury or fatalities either to workers at the vertical assembly building or further away on the site, or to off-site residents. It can also be noted that control of milk might be required, depending upon the conditions prevailing at the time of the accident. In general, only an accident occurring under moderately stable atmospheric conditions with an onshore wind will result in the necessity for any control actions in the uncontrolled areas surrounding the Missile Test Center. Since moderately stable conditions are restricted to a great extent to the nighttime hours, this would indicate a desirability (but not a necessity) for restricting operations which might result in such an accident during these hours.

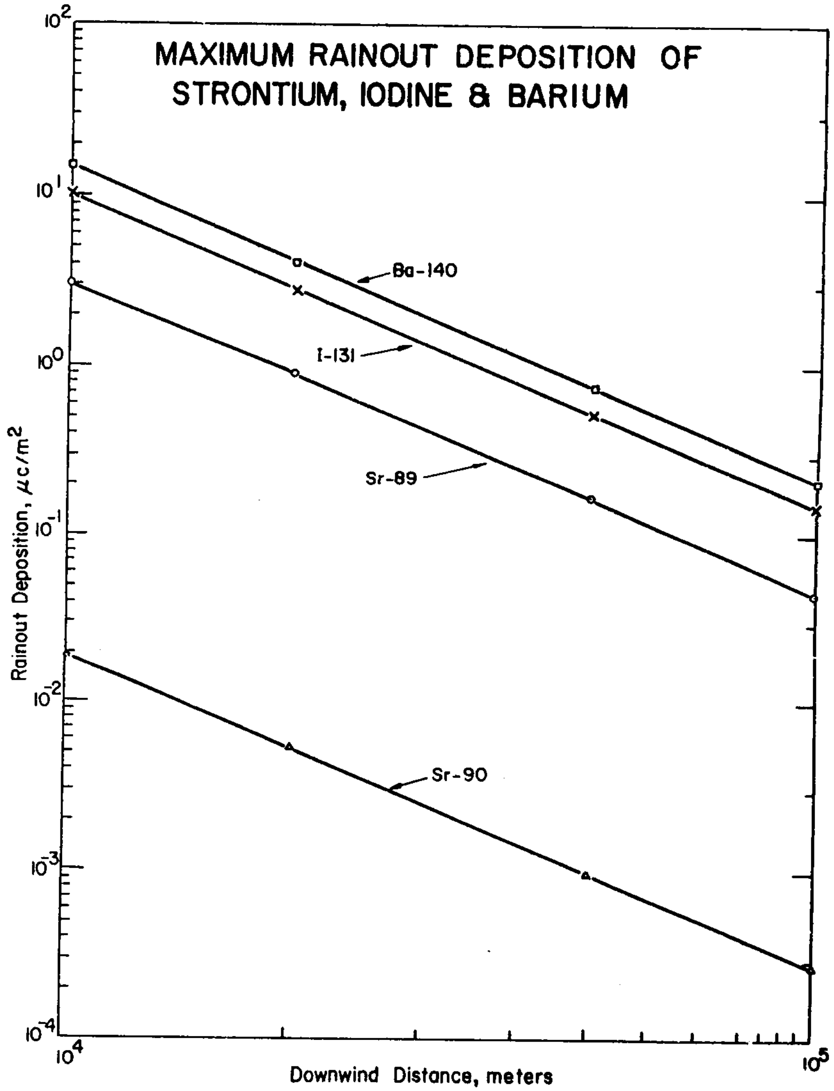


Figure IV-26

The major control indicated as necessary by these dose studies is that to be applied to milk from cattle in the area of iodine deposition downwind from the accident, which may extend more than 60 miles from the site. No control action appears necessary for cloud doses or thyroid doses from inhaled material, nor need more than surveillance be maintained over surface water supplies such as that provided from Lake Washington and possibly from Lake Poinsett. Monitoring would also be indicated as desirable for processors of agricultural products prior to their distribution to the public, although, in general, sufficient time should be available to delineate those farms whose crops are contaminated before harvesting and to restrict the sale or consumption of such crops.

The doses to on-site personnel following such an accident would be more severe than those experienced by off-site individuals. Perhaps the single, most important parameter for on-site hazard evaluation is the location of the reactor at the time of the accident. If the reactor is in a shielded area, such as is planned for the nuclear assembly building, the exposures should be minimized; if the reactor is on or immediately adjacent to the launch pad at the time of the accident, doses at the assembly area will be high, but not unreasonable. By combining consideration of the doses and the separation distances, it is possible to delineate the confines of an area within which an accident will result in doses at the vertical assembly building or other areas which would not exceed specified values. As an example of such delineation, a limit line for accident location is shown in Figure IV-27 within which doses at the various buildings of Complex 39 will not exceed 25 roentgens whole body radiation, or 300 rad to the thyroid. These doses are based upon the most conservative assumptions made in the study above. No deposition is assumed; 20 percent core vaporization is presumed to accompany the accident and moderately stable atmospheric conditions are presumed to prevail. The gamma dose limit derives from the sum of the prompt radiation and the dose from cloud passage, but not from deposition on the ground.

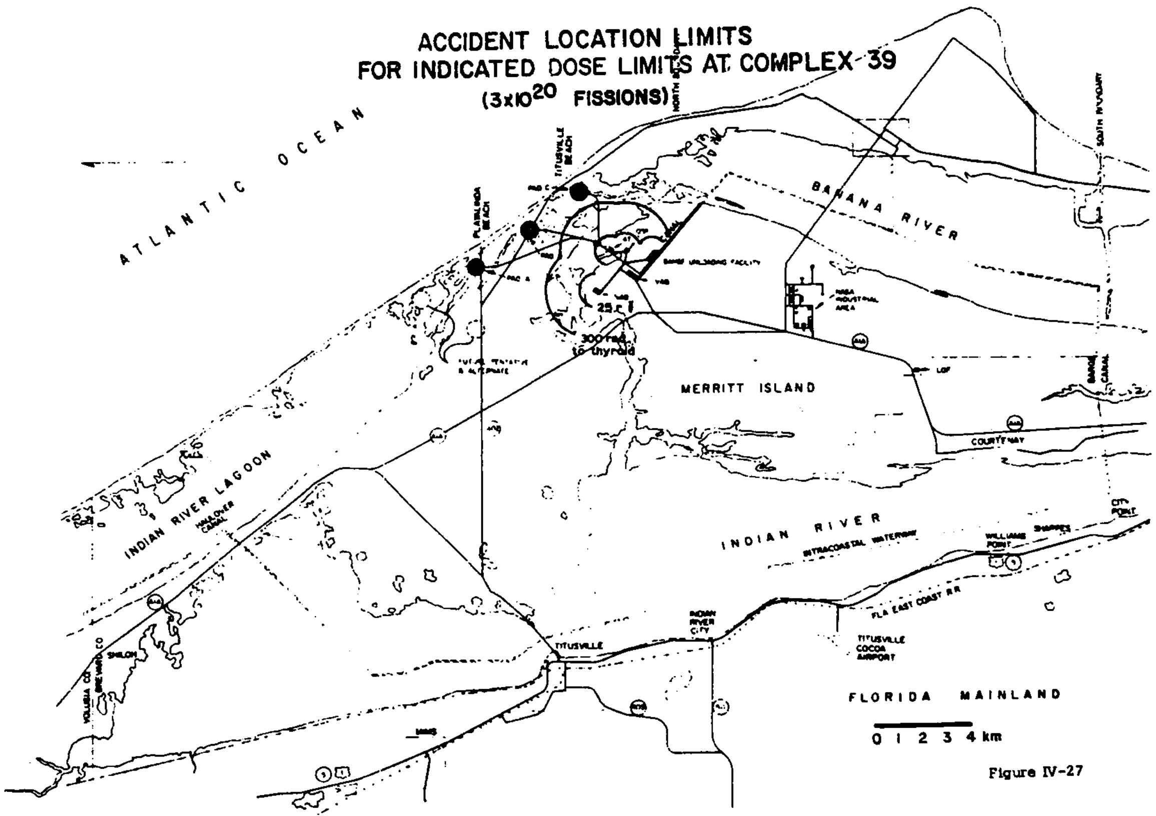

ACCIDENT LOCATION LIMITS
FOR INDICATED DOSE LIMITS AT COMPLEX 39
(3×10^{20} FISSIONS)
ATLANTIC OCEAN
BANANA RIVER
MERRITT ISLAND
INDIAN RIVER LAGOON
INDIAN RIVER
INTRACOASTAL WATERWAY
25 r
300 rad to thyroid
NASA INDUSTRIAL AREA
COURTENAY
TITUSVILLE
INDIAN RIVER CITY
FLA EAST COAST RR
TITUSVILLE COCOA AIRPORT
FLORIDA MAINLAND
0 1 2 3 4 km

Figure IV-27

From this figure it may be seen that, if one hypothesizes the accident occurring as a result of impaction in water or on land following booster failure in the early stages following lift-off, the use of Pad A provides more leeway than do Pad B or C for this particular hazard. It is also quite clear that iodine again produces a more limiting circumstance than does the whole body gamma dose. If better information were available on the deposition of iodine to be expected on the vegetation existing in the immediate vicinity of the launch area, these limits could undoubtedly be reduced to approach more closely the values for whole body gamma dose and hence afford a greater degree of leeway in range safety planning for this particular hazard.

In general, however, it appears that no insurmountable hazards are introduced by an accident of this magnitude, either to on-site or to off-site individuals, although administrative control will be necessary to assure that the effects of any such accident are minimized.

Recent estimates by LASL have indicated, on a preliminary basis, that a larger excursion is liable to occur from a high velocity, nozzle-down water entry of the nuclear stage. In this case, an excursion on the order of 10^5 MW-sec is possible with an explosive disruption of the core prior to complete immersion and a consequent release of a substantial portion of the fission products to the atmosphere. Some of the fission products would enter the water directly, and some would be entrained by the spray of water created by the impact and excursion, but much of the volatile inventory would be released. A significant fraction of the non-volatile elements would also be released, either by vaporization of the core, or scattered in-core fragments.

This accident requires analysis in detail, for which no time has been available. However, as an initial estimate, the doses presented in this section, multiplied by a factor of ten, may be used.

D. BOOSTER FAILURE ACCIDENTS

1. General

This accident is presumed to involve a nuclear excursion accompanied and in some cases initiated by the release of a significant amount of chemical energy from a booster explosion. This could be presumed to occur at any time following fueling until the vehicle is well along its trajectory downrange. However, the effects are most significant if the accident should occur at or shortly above the ground.

Two factors play a more significant role in relating the environmental effects to the source: the first concerns the height to which the cloud containing radioactive material (mostly fission products) and beryllium rises before horizontal transport and diffusion begins; the second concerns the distribution of this material in the form of gas or different sized particles in the cloud.

The vaporized and solid fractions of the core impose mutually exclusive requirements with respect to desirable conditions. Horizontal transport of particles is minimized by restricting the height of rise. On the other hand, diffusion of very fine particles and gases is enhanced by an increase in the effective height of release. To provide an indication of the possible scope of the problem, the booster explosion is presumed to occur on the pad, and the resulting effective release height is the minimum, resulting only from the rise of the cloud due to thermal effects.

2. Source Description

a. Magnitude of Release

As discussed in Section IV-B, the behavior of the reactor under conditions accompanying a booster explosion are highly uncertain. The magnitude, and even the occurrence, of an excursion are open to question. Under the assumption made herein, however, an excursion approximating 3×10^{21} fissions (about 10^5 MW-sec) is hypothesized coincident with a booster explosion equivalent to 10^6 pounds of TNT.

The fission products generated were calculated for 3×10^{21} fissions from the WANL tabulation presented in Table IV-9, as in the previous case. Additionally, 10 percent of the beryllium reflector, some 230 pounds, was assumed to be vaporized, and released to the environment as very fine particles.

Under the hypothesized conditions, sufficient heat is liberated by the excursion alone to completely vaporize the core if uniformly distributed. However, for this analysis, it will be assumed that the core is fractured according to the distribution for a 7 mm maximum diameter particle as shown in Figure III-7, and that the volatile elements only are released as gases from the core material. This results in a release consisting of volatile fission products* and beryllium diffusing as if they were gases, and a residue of nonvolatile fission products contained in fragments of core material covering a range of particle sizes.

b. Cloud Characteristics

Two factors are of importance with respect to the cloud resulting from the hypothesized accident: its volume and height. The cloud volume at the altitude at which horizontal movement becomes predominant is a measure of the initial dilution of materials in the cloud. Cloud height, as indicated above, plays a major role in determining the ground level distribution of material carried aloft in the cloud.

Cloud volume can be determined analytically or empirically - an empirical approach has been preferred,[98] and was used in this evaluation. Measurements of cloud volume were made from two series of photographs of propellant explosion clouds produced by A. D. Little.[80]

These explosions of 10,700 and 27,000 pounds of high explosive (H.E.) equivalent yielded stabilized cloud volumes of 1.4×10^7 and 3.9×10^7 cubic meters, respectively. On

*See Table IV-8 for listing of "volatile fission products."

this basis, an approximate cloud volume of 1.4×10^3 m^3/pound of H.E. was derived. With a total energy yield for this hypothesized incident of about 1×10^6 pounds of H.E. equivalent, the cloud volume at stabilized height becomes about 1.4×10^9 cubic meters. Using empirically derived equations[99] for nuclear weapon detonation clouds, a cylindrical cloud with a volume of 1.86×10^9 m^3 is calculated, providing a reasonable degree of confirmation for the photographic measurements.

The rise of a cloud can also be determined either analytically or empirically - neither method producing results of great precision.[35] Using a relationship by Sutton[35] for a heat liberation of about 5×10^{11} calories results in a computed mean altitude for the cloud of about 3,700 m. LASL[100] has compiled data on documented cloud heights from weapons tests as a function of yield, shown in Figure IV-28. For a heat yield of 5×10^{11} calories (500 tons of H.E.), it may be seen that the cloud would range between 6,300 - 14,000 feet (1,900 - 4,300 meters). The equations used above for cloud volume produce elevations for bottom and top of 5,400 and 12,000 feet (1,650 and 3,650 meters). From these data, a value of 3,500 meters for mean cloud rise was selected.

3. Dose-Distance Relationships

a. Volatile and Fine Particulate Materials

As in the previous representative accident considered, a number of potential radiation exposures must be analyzed for significance in this case. It is possible, however, by considering the initial cloud (dilution) volume, and the effect of the initial height to eliminate a number of dose routes which were significant in the previous case.

The initial cloud volume of 1.4×10^9 m^3 provides an initial dilution which can be expressed in a number of ways. For this analysis, the assumption of a virtual point source x_o meters up wind is made such that a cloud of the proper dimensions results at $x = 0$ (the release point). The virtual source distance, x_o, is selected such that $y_o z_o = R^2$, where $y_o = 2.15\ \sigma_z$;

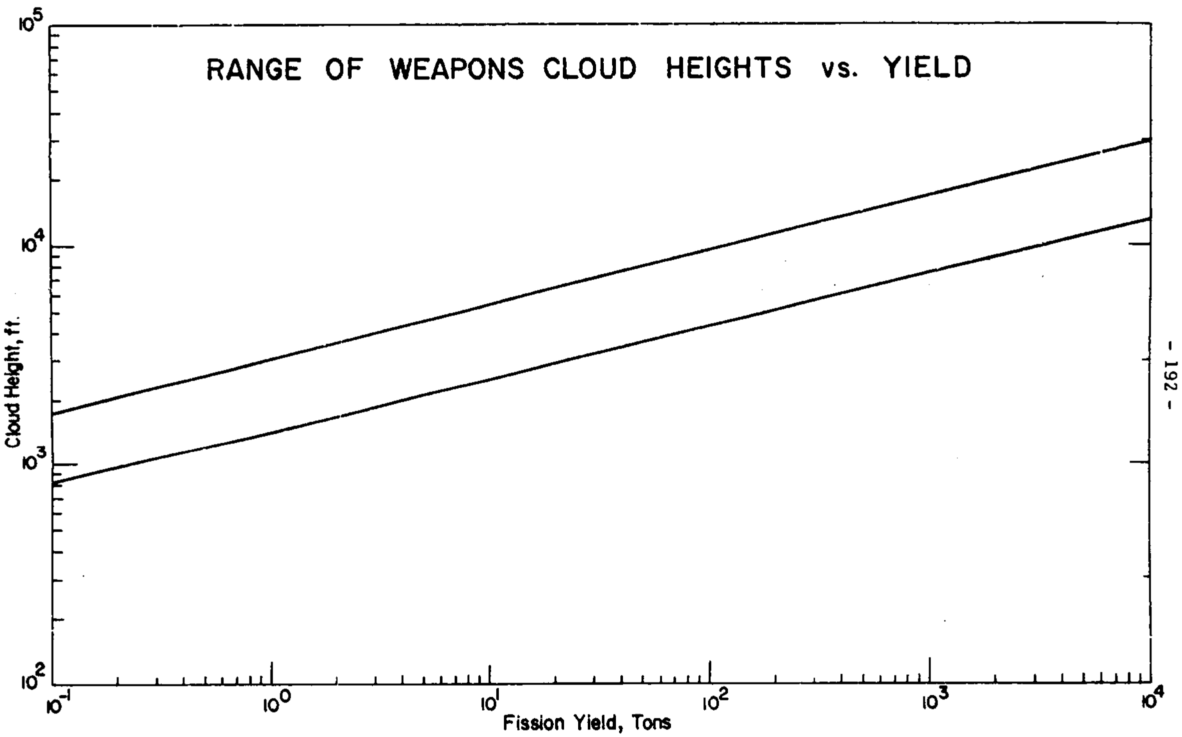

RANGE OF WEAPONS CLOUD HEIGHTS vs. YIELD
10^5
10^4
10^3
10^2
Cloud Height, ft.
10^{-1}
10^0
10^1
10^2
10^3
10^4
Fission Yield, Tons

Figure IV-28

$z_o = 2.15\ \sigma_z$; and $R^2 = (3 \times \text{Volume}/4\ \pi)^{2/3}$. Then x_o can be computed using values for σ_y and σ_z appropriate to the stability patterns examined.

For this case, the stable atmosphere is not considered to apply, since the cloud from an explosion of this magnitude would probably penetrate the inversion and diffusion from above would be hindered until the inversion layer was dispersed. Since an analytical treatment of this case would be based on a number of highly tenuous assumptions, it was not considered further.

For moderately unstable (B) and neutral (D) atmospheres, values of x_o of 2×10^3 and 1.3×10^4 meters, respectively, were obtained. If Equation III-4 is solved for the point at which ground concentration is a maximum (by iteration, since explicit functions for σ_y and σ_z are not available), a distance of some 2.5×10^6 meters (or about 150 miles) is obtained under neutral conditions. At this distance (and at a closer distance under lapse conditions), the maximum ground level concentration (or time-integrated concentration for a puff release) is extremely low.

The relationship for χ_{max} presented by Gifford,[43] assuming $\sigma_y = \text{constant} \times \sigma_z$, is

$$\chi_{max} = \frac{2Q}{\pi h^2 e \bar{u}} \quad \frac{\sigma_z}{\sigma_y} \qquad \text{(IV-2)}$$

Using h = 3,500 meters, $\bar{u}$ = 3 m/s; and $\sigma_z/\sigma_y \sim 0.1$, a value of χ_{max}/Q of about 6×10^{-10} sec/m^3 is obtained. This maximum value is three to seven orders of magnitude below the values pertaining to the previous, ground level release at much closer distances. Therefore, although the fission product release is ten times greater in this case, it would appear that external and internal doses from cloud passage and deposition would be insignificant, at least insofar as the fractions of fission products which are truly gaseous or so fine as to act like gases are concerned.

Using the extremely conservative assumption that 10 percent of the beryllium reflector is dispersed as particles of respirable size (<10 μ), the maximum exposure to beryllium can be calculated for this situation. With a value for Q of 1×10^{11} μg (~230 pounds) and $\chi/Q = 6 \times 10^{-10}$ sec/m^3, the maximum ground level exposure would be 60 μg-sec/m^3. This is well below the recommended[101] environmental limit of 0.01 μg/m^3 as a daily average (864 μg-sec/m^3) on a continuous basis, and it would therefore appear that beryllium should provide no source of hazard.

If the beryllium release (Q) is assumed to remain constant at 230 pounds and the acute exposure value of 750 μg-min/m^3 (45,00 μg-sec/m^3) recommended by AIHA[101] is chosen, then $\chi_{max}/Q = 4.5 \times 10^4/10^{11} = 4.5 \times 10^{-7}$ sec/m^3. From Equation IV-2, the minimum height of release at which this ground level integrated concentration would occur anywhere is about 200 meters. Using the previously cited Sutton relationship for cloud rise, this would require an energy release of less than 10^8 calories. Since the nuclear excursion liberates about 2×10^{10} calories, a release of less than 1 percent of the deposited nuclear energy alone would provide a sufficient cloud rise to preclude an acute beryllium problem at any location. It should be recognized, however, that the shattering and vaporization of the quantity of beryllium hypothesized in the source would probably require a much greater energy release.

The novel hazard introduced by this accident class is that resulting from the dispersion of the core in large (greater than 10 μ) particulate form. Sufficient energy is available to shatter, if not vaporize, the core materials, and the remainder of this analysis is directed at the "fallout" problem.

b. Large Particle Distribution and Dose

Using the particle size distribution and particle transport relationships developed in Section III and the height of release considered in this section, a ground level particle size distribution is derived. Additional assumptions necessary are those relating to wind speed and shear. Maximum local contamination will occur with no wind, in which case particles will fall back to the area of origin - hypothetically

over a radius equal to that of the cloud, some 700 meters - with the largest particles predominating at the center.

An estimate of the locus and time of deposition of various sizes of particles from the data in Figure III-6 and III-7 is presented in Table IV-11 for surface wind speeds of 1.3, 2.8 and 5 meters per second and a release height of 3,500 meters. Using a core weight of 1.3×10^6 gms and the particle size distribution for 10 pound H.E. equivalent and a 7 mm maximum size (Figure III-7), an estimate of particle density per unit area was made by arbitrarily assuming a lateral spread of 15°. Number density and weight density are listed in Table IV-12 for the 1.3 m/s wind speed, as a function of particle size range. These densities are inversely proportional to the square of the wind speed, so values for other wind speeds may be readily obtained for the same release height and lateral spread.

Skin dose determinations were based on the method of Hines and Brownell[55] for spherical particles. Residual (non-volatile) beta power was determined by difference between the WANL volatile beta power and the Martin Company total beta power for 3×10^{21} fissions, and is plotted in Figure IV-29 as a function of time. Residual beta power per unit weight of core material was derived assuming a core weight of 1.3×10^6 gms. Beta energy spectra were determined for the times of interest from data presented by Fish and Patterson.[54] The results of the calculation of the beta dose rate at the surface of spherical particles are presented in Table IV-13 and Figure IV-30.

It can be seen from these data that particles on the order of tens of microns in diameter can produce some skin damage, and that particles which may be carried off-site by modest winds ($\lesssim$ 500 μ) can inflict quite severe epidermal burns and ulceration - with doses $> 10^5$ rad resulting from continuous contact with 200 μ particles.

The skin doses from larger particles which fall on-site can be limited to a considerable extent by exercising control over personnel location and emergency showers.

TABLE IV-11

HORIZONTAL TRANSPORT OF PARTICLES

(Release Height: 3500 m; ρ = 2.0)

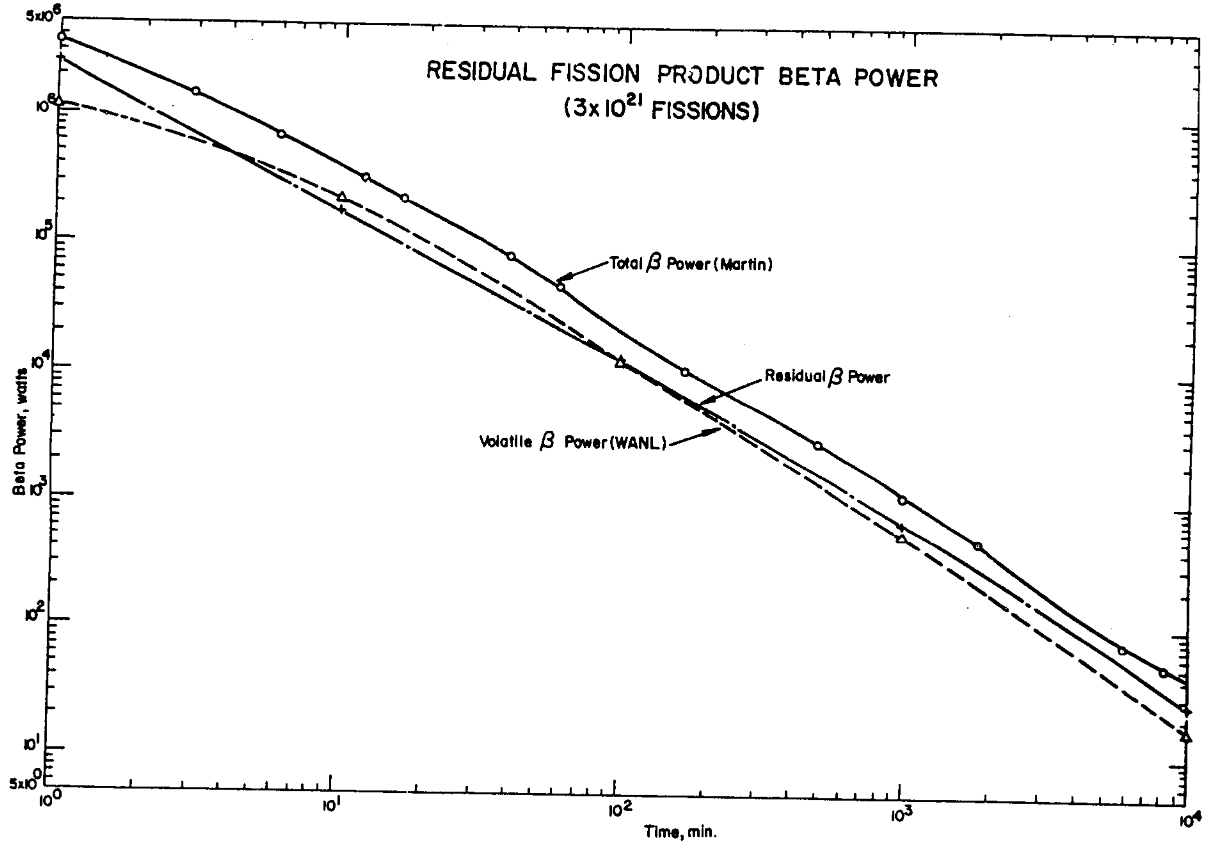
Particle Diameter, µm	Time of Fall min.	Horizontal Transport, meters V_s = 1.3 m/s	V_s = 2.8 m/s	V_s = 5.0 m/s
6000	3.43	575	1,240	2,210
2000	6.0	950	2,040	3,650
1000	11.7	1,940	4,180	7,470
600	19.7	3,390	7,300	13,000
200	66.7	11,000	23,700	42,300
100	150	25,400	54,700	98,000
75	260	43,400	93,500	167,000
50	580	97,500	210,000	375,000
25	2,860	382,000	822,000	1,470,000

TABLE IV-12

DEPOSITION DENSITY OF PARTICLES

(3500 m release height; lateral spread 15°; V_s = 1.3 m/s)

Size Range µm	Average Density Number/m^2	gm/m^2	Deposition Range, m
6000 - 7000	6.5	1.8	0 - 575
2000 - 6000	98	6.6	575 - 950
1000 - 2000	170	0.63	950 - 1,940
600 - 1000	210	0.13	1,940 - 3,390
200 - 600	190	1.3×10^{-2}	3,390 - 11,000
100 - 200	260	9.5×10^{-4}	11,000 - 25,400
75 - 100	180	1.8×10^{-4}	25,400 - 43,400
50 - 75	87	2.3×10^{-5}	43,400 - 97,500
25 - 50	26	1.4×10^{-6}	97,500 - 382,000



RESIDUAL FISSION PRODUCT BETA POWER
(3×10^{21} FISSIONS)
Total β Power (Martin)
Residual β Power
Volatile β Power (WANL)
Beta Power, watts
Time, min.

Figure IV-29

TABLE IV-13

SURFACE DOSE RATES FOR SPHERICAL BETA SOURCES

Particle Diameter, μm	$t = 10^1$ min		$t = 10^2$ min		$t = 10^3$ min		$t = 10^4$ min	
	R_β Surface / $R_\beta \infty$	R_β Surface rad/hr	R_β Surface / $R_\beta \infty$	R_β Surface rad/hr	R_β Surface / $R_\beta \infty$	R_β Surface rad/hr	R_β Surface / $R_\beta \infty$	R_β Surface rad/hr
6000	0.33	1.7×10^7	0.36	1.2×10^6	0.40	7.6×10^4	0.47	3.6×10^3
2000	0.15	7.5×10^6	0.18	5.9×10^5	0.24	4.6×10^4	0.41	3.1×10^3
1000	0.075	3.8×10^6	0.093	3.1×10^5	0.14	2.7×10^4	0.34	2.6×10^3
600	0.045	2.3×16^6	0.055	1.8×10^5	0.080	1.5×10^4	0.26	2.0×10^3
200	0.015	7.5×10^5	0.019	6.3×10^4	0.027	5.1×10^3	0.11	8.4×10^2
100	0.0075	3.8×10^5	0.0093	3.1×10^4	0.014	2.7×10^3	0.06	4.6×10^2
75	0.0055	2.8×10^5	0.0070	2.3×10^4	0.010	1.9×10^3	0.040	3.0×10^2
50	0.0039	2.0×10^5	0.0047	1.6×10^4	0.0063	1.2×10^3	0.025	1.9×10^2
25	0.0019	9.5×10^4	0.0024	7.9×10^3	0.0034	6.5×10^2	0.015	1.1×10^2
$R_\beta \infty$ watts/gm rad/hr	0.14 5.0×10^7		9.2×10^{-3} 3.3×10^6		5.2×10^{-4} 1.9×10^5		2.1×10^{-5} 7.6×10	

Notes: $R_\beta \infty$ = residual (non-volatile) beta power per gram from 3×10^{21} fissions
1 watt per gram = 3.6×10^8 rad/hr

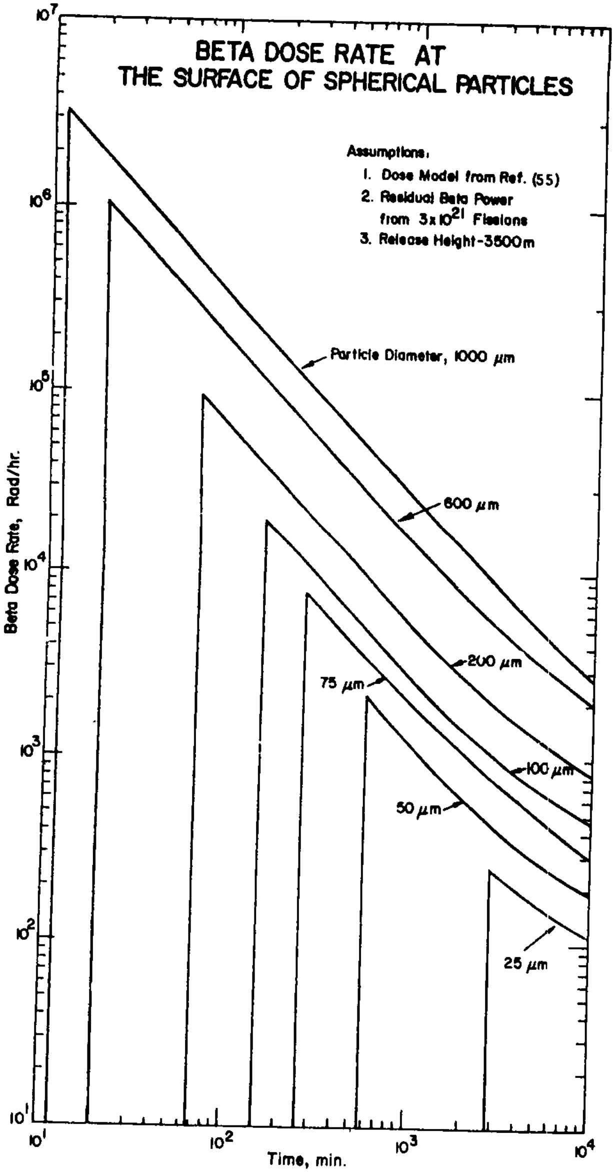


Figure IV-30

Gamma dose rates from surface deposition can be estimated from the weight density shown in Table IV-12 and the residual gamma power. Extrapolating from the data shown in Figure IV-11, residual gamma power per gram of core material is calculated as:

t, min	Residual Q_γ, watts/gm
10^0	.27
10^1	4.2×10^{-2}
10^2	5.8×10^{-3}
10^3	4.2×10^{-4}
10^4	3.1×10^{-5}

The particles are assumed to deposit in a 15° sector downwind. There is a fractionation of particles with regard to size versus distance, the larger ones falling close to the source, as shown in Table IV-12.

For ease of calculation deposition is assumed to be uniform within a circle with diameter equal to the arc length and at a value corresponding to the distance of the arc from the source. The number of grams deposited per square meter is indicated in Table IV-12, and the fallout dose was computed using a relationship identical in form to Equation III-7. The results are indicated in Figure IV-31 for the 1.3 m/s surface wind, as a function of distance and time.

The gamma dose rates are strongly affected by the particle size distribution and the wind speed. It can be noted in Table IV-12 and Figure IV-31 that a peak in a deposition occurs in the range of 400-1,000 meters, due entirely to the particle size distribution assumed for this analysis. An increase in wind speed to 2.8 m/s and 5 m/s will reduce the density of deposition and the resulting doses by factors of about 5 and 15, respectively; the areas affected will increase by about the same factor. The fallout doses are also approximately inversely proportional to the square of the release height.

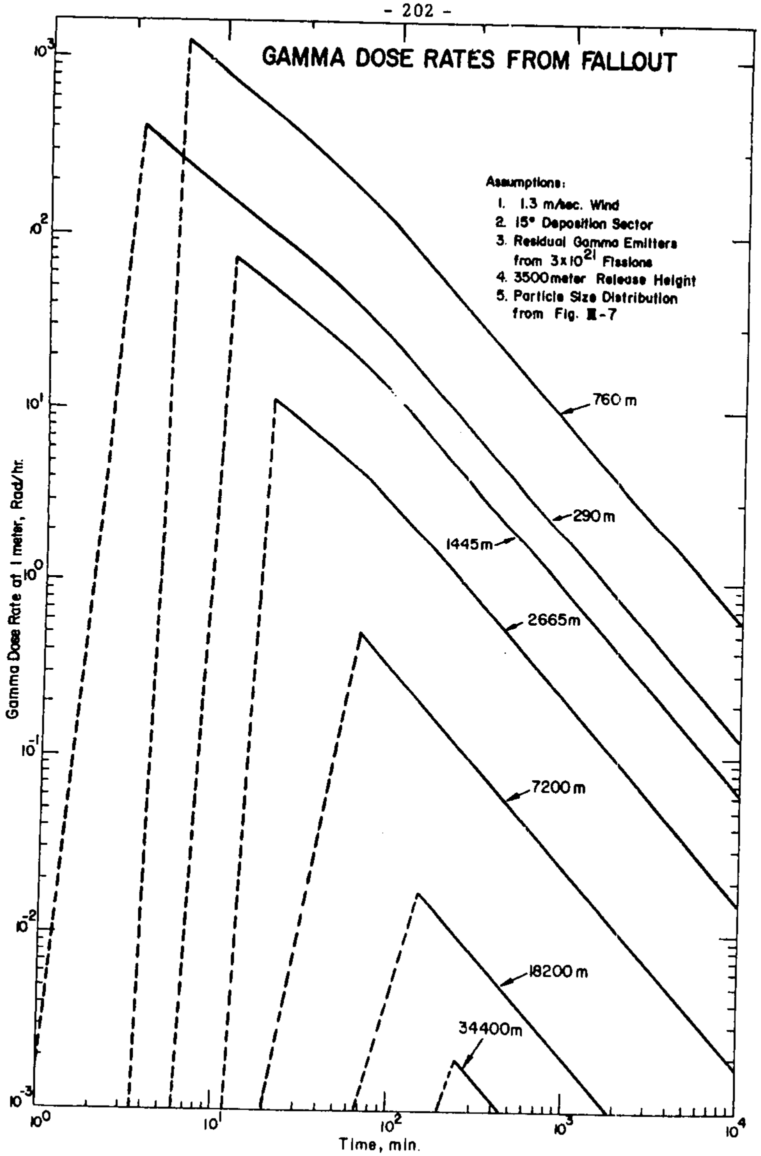


Figure IV-31

Since ingestion doses imply some degree of solubility, the significance of particulate fallout in surface water or via other food chains is dependent to a large extent on the leaching rate of selected fission products from graphite. Although data are being collected to this end by NRDL, no information is presently available that would make an estimate possible. It can be noted, however, that many of the more toxic radionuclides are almost certain to be evolved as vapors, and hence, would not be present in the residual contamination.

Inhalation of small particulates might engender some damage to bronchial, lung, or other tissues. The uncertainties in this analysis have been indicated by Fish and Patterson. It appears that the skin doses are limiting in consideration of the single-particle problem.

A potential hazard may also result from the scattering of unirradiated fuel by a non-nuclear energy release which fragments the core. In this event, the hazard arises from inhalation of enriched uranium as both a radiological and chemical toxicant. For an initial estimate of this hazard, it is assumed that 10 percent of the fuel inventory is in the form of particles 10 μm or less in size and that the material may be either soluble or insoluble.

The occupational chemical-based toxicity MAC (maximum allowable concentration) for inhalation of uranium on a continuous basis is 50 $\mu g/m^3$. From Equation III-8 and the appropriate constants for Uranium-235 in the soluble (critical organ-kidney) and insoluble (critical organ-lung) forms, acute intake values corresponding to doses of 1.5 rem per year can be calculated. These are 3.2×10^{-7} curies and 3.4×10^{-8} curies for the kidney and lung, respectively.

For a source, Q, of 1.89×10^4 gm (0.0406 curies) of Uranium-235 corresponding to 10 percent of the core, and a χ_{max}/Q of $\sim 6 \times 10^{-10}$ sec/m^3, used previously, a maximum value for χ of $1.89 \times 10^{14} \times 6 \times 10^{-10} = 1.23 \times 10^5$ ug-sec/m^3 would be obtained for the booster explosion case. This is about a factor of 10 less than the permissible occupational intake for 8 hours (50 ug/m^3 $\times 2.88 \times 10^4$ sec $= 1.44 \times 10^6$ ug-sec/m^3) based on chemical toxicity. With a breathing rate of 3.5×10^{-4} m^3/sec, the total intake during cloud passage in this case would be ~40 μg of Uranium-235 (or 8.5×10^{-11} curies).

With no cloud rise and assuming the lung dose is controlling, the value of χ/Q required to meet the single intake value of 3.36×10^{-8} curies is:

$$\chi/Q = \frac{(\chi \times \text{Breathing Rate})}{Q \times \text{Breathing Rate}} = \frac{3.36 \times 10^{-8}}{.0406 \times 3.5 \times 10^{-4}} = 2.36 \times 10^{-3} \text{ sec/m}^3$$

Based upon the most restrictive meteorological conditions and the dispersion model of ORO-545,[38] this value would be reached or exceeded only at distances of 500 meters or less from the point of release.

4. Summary - Booster Failure Accident

In an accident of the type hypothesized, with a substantial amount of additional energy provided by chemical reactions of propellant materials, the thermal cloud rise appears sufficiently great to preclude significant hazards to individuals from volatilized fission products, unirradiated uranium, or beryllium. If, on the other hand, nonvolatile fission products remain in core material particles in the range of 10-1,000 um, a significant hazard can be generated both by fallout gamma fields and by skin exposure to single particles. In this regard it should be noted that a reduction in the fission product inventory by the assumption of an excursion magnitude lower by a factor of 10 will still predict substantial problems, both on- and off-site, particularly from beta dose to the skin of exposed individuals. Doses greater than 1,000 rads can be expected to produce significant injury to the skin,[102] although effects will vary greatly with the beta energy.

E. MARINE RELEASE ACCIDENT

1. Source Description

a. Magnitude of Excursion

As described earlier, the estimate of energy release in the event of a water immersion accident is critically dependent on the mode and rate of entry of the water into the reactor core. The estimate has been made that the energy release would approximate 10^5 MW-sec from a high velocity, nozzle-down entry, the "worst case." In the event of this accident, the reactor would probably be disassembled and fragmented before a substantial part of the core was immersed, and the fission products would be released primarily to the atmosphere.

In order to obtain an estimate of the effect of a release to the water environment in the vicinity of the launch site, a smaller excursion, 3×10^{20} fissions (about 10^4 MW-sec), was chosen for study.

b. Fission Product and Toxic Material Release

In view of the high temperature obtaining in excursions of this size, the assumption is made of 100 percent fission product release following impact and immersion in the ocean or other body of water. The rare gases are assumed to be released to the atmosphere and dispersed in accordance with the patterns described in Section C above. Remaining fission products generated in the excursion are assumed to be readily soluble in the water. These are acted upon by the currents that tend to transport and disperse soluble material in the ocean.

An alternate approach consists of treating the complete retention of the fission product core inventory (less the rare gases) in particles of the graphite matrix which is distributed on the sea bed with a particle size distribution shown in Figure III-7. The problem here is created by the washup of these particles on the shore, presenting a potential external radiation exposure to beach bathers and souvenir hunters.

c. Spatial Distribution

The energy release from the water immersion accident is assumed for the purposes of this analysis to be relatively well confined. It is recognized that, in an actual event of this type, fractionation of released fission products would occur between the atmosphere and aqueous phase. To analyze the effect on the marine system, release to the atmosphere is ignored except for noble gases. If volatile materials were released to the atmosphere, it is expected that the transport and dose models would follow those used in Section IV-C above for the nuclear criticality accident. In Section III-B, assumptions were made of two initial volumes of uniform concentration represented by two cylinders 10 m and 100 m in diameter and of 10 m in depth, 7.85×10^5 kg and 7.85×10^7 kg, respectively. (Here liters and kilograms are used interchangeably.) This was done to provide the initial mechanical dilution prior to diffusion and turbulent mixing caused by the dynamic forces in the marine environment.

2. Location

Essentially there are two general treatments used in analyzing the effects of the water immersion accident on the marine environment. In the coastal waters and the Gulf Stream, dispersion of the fission product inventory into a soluble diffusing cloud which obeys the Joseph and Sendner model previously described in Section III-B was used. In the event of the accident occurring in the region directly influenced by the Gulf Stream, the contaminant cloud will be transported intact at an average speed of about 3 1/2 knots.

A different situation is raised when the potential accident occurs in the inland rivers and launch site swamps and creeks. Table III-2 is a summary of the area, volume, and depth of separate reaches of the inland river basins around Cape Canaveral which are divided by the man-made causeways and natural barrier ridges in the region.

3. Dose Relationships

a. External Dose

Exposure to personnel from direct radiation, cloud passage and particle fallout have been treated previously in Section III-C. As mentioned above, this case is intended to determine doses resulting from injection into the marine environment only. It is recognized that, in fact, airborne material may be generated; doses from these would not be greater for this magnitude of release than those treated for the nuclear criticality accident at a similar location. Immersion of swimmers is the only potential source of external exposure that will be considered here. Other second order effects such as exposure to contaminated debris washed up on beaches, fishing gear, etc., were not included in this study.

Applying Equation III-15a for the dose rate to a person immersed in a herispherical infinite fluid to the separate situations of the inland waterways and the ocean leads to results which are presented in Table IV-14. The dose rates for the uniformly dispersed cases in the inland waterways at 10 and 100 minutes are probably low by one or two orders of magnitude due to the finite time required to obtain uniform mixing. However, this does not present an insurmountable problem for area entry or to apply countermeasures. Dose rates in the ocean are quite reasonable and are amenable to early entry if necessary.

b. Internal Dose

Basic guidelines for the evaluation of the potential hazard to man from ingestion of radioactive contaminants in seafood have been discussed in Section III-C. This discussion was based on the comprehensive treatment of the problem of marine ecological transport of radionuclides as presented in the Isaacs report.[69]

A comparison of the WANL fission product inventory in Table IV-9 with the nuclides listed in the Isaacs report yields only fifteen matching nuclides, although these are among the most

TABLE IV-14

IMMERSION DOSE RATES

Inland Waterway	Volume, cm^3	Dose Rates - r/hr at Decay Times of 10^1 min	10^2 min	10^3 min	10^4 min
Mosquito Lagoon	1.16×10^{14}	6.4×10^{-2}	6.5×10^{-3}	3.5×10^{-4}	1.8×10^{-5}
Indian River					
N. of Titusville	1.62×10^{14}	4.6×10^{-2}	4.6×10^{-3}	2.5×10^{-4}	1.3×10^{-5}
Titusville to Cocoa	2.58×10^{14}	2.9×10^{-2}	2.9×10^{-3}	1.6×10^{-4}	8.1×10^{-6}
Cocoa to Eau Gallie	1.41×10^{14}	5.3×10^{-2}	5.4×10^{-3}	2.9×10^{-4}	1.5×10^{-5}
Eau Gallie to Melbourne	3.92×10^{13}	1.9×10^{-1}	1.9×10^{-2}	1.0×10^{-3}	5.3×10^{-5}
Banana River					
W. of Cape Canaveral	1.21×10^{14}	6.1×10^{-2}	6.2×10^{-3}	3.4×10^{-4}	1.7×10^{-5}
W. of Artesia	3.92×10^{13}	1.9×10^{-1}	1.9×10^{-2}	1.0×10^{-3}	5.3×10^{-5}
W. of Patrick AFB	1.17×10^{14}	6.4×10^{-2}	6.5×10^{-3}	3.5×10^{-4}	1.8×10^{-5}
Ocean					
Case A	7.85×10^{10}	9.4×10^{1}			
Initial Volume: 7.85×10^8 cm^3 @1 min	7.85×10^{12}		9.6×10^{-2}		
	7.85×10^{14}			5.2×10^{-5}	
	7.85×10^{16}				2.7×10^{-8}
Case B	7.85×10^{12}	9.4×10^{-1}			
Initial Volume: 100 x Case A	7.85×10^{14}		9.6×10^{-4}		
	7.85×10^{16}			5.2×10^{-7}	
	7.85×10^{18}				2.7×10^{-10}
Total $\beta+\gamma$ power at respective times	---	4.1×10^4w	4.2×10^3w	2.25×10^2w	1.2×10^1w

significant, biologically. These are listed in Table IV-15 with the corresponding activities for 10^3 and 10^4 minutes after the accident, the maximum permissible concentration in sea water (MPCC) and peak concentrations in sea water for each nuclide at these times for two cases of initial dilution. The diluting volumes are identical with those used in the preparation of Table IV-14 for the ocean portion of the table. It should be noted that peak concentrations in the center of the diffusing volume are used rather than any other point in the spatial distribution.

The MPCC represents that concentration in the sea water below which the allowable radiation exposure for any individual cannot be exceeded as a result of the consumption of marine products. By comparing the peak concentrations of radionuclides in Case A (initial dilution in 10 m diameter x 10 m depth) at 10^3 minutes (approximately 17 hours), it is found that five nuclides (Ruthenium-106, Iodine-131, Barium-140, Lanthanum-140, and Cerium-141) approach within an order of magnitude and two nuclides (Ruthenium-103 and Cerium-144) exceed their corresponding MPCC values. All of these elements, with the exception of iodine and barium, were found to be primarily in the particulate state by Greendale and Ballou in a simulated study of an underwater detonation of an atomic bomb.(103) This would indicate that the significant link in the marine ecological chain would be the zooplankton (some of which feed on particulate matter) and larger filter-feeders.(104)

Many of the radioisotopes concentrated by plankton are biologically important to man. However, they do not necessarily have long biological half-lives in man. Nuclides that may be present in plankton but not mentioned above due to their exclusion from quantitative consideration in the Isaacs report are Molybdenum-99 and Technitium-99m, a fission product pair with physical half-lives of 67 hours and 6 hours, respectively. Their short half-lives preclude concern at this time. Ruthenium and its daughter rhodium have relatively short half-lives in man (20 days) which reduces some of the concern that might be engendered by a cursory look at the comparison between MPCC and peak nuclide concentration at 10^3 minutes for Case A.

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TABLE IV-15

SIGNIFICANT FISSION PRODUCT CONCENTRATIONS IN SEA WATER

	Activity-μc		MPCC	Peak Concentration $\mu c/kg$			
				Case A		Case B	
	10^3 min	10^4 min	$\mu c/kg$	10^3 min	10^4 min	10^3 min	10^4 min
Sr-89	6.1×10^{7}	5.4×10^{7}	8.7×10^{0}	7.8×10^{-5}	7.1×10^{-7}	7.8×10^{-7}	7.1×10^{-9}
Sr-90	3.7×10^{5}	3.7×10^{5}	3.4×10^{-2}	4.7×10^{-7}	4.7×10^{-9}	4.7×10^{-9}	4.7×10^{-11}
Y-91	1.8×10^{7}	2.4×10^{7}	7.0×10^{-2}	2.3×10^{-5}	3.1×10^{-7}	2.3×10^{-7}	3.1×10^{-9}
Zr-95	6.2×10^{7}	5.7×10^{7}	6.0×10^{-4}	7.9×10^{-5}	7.3×10^{-7}	7.9×10^{-7}	7.3×10^{-9}
Nb-95	1.6×10^{5}	3.6×10^{6}	5.0×10^{-3}	2.0×10^{-7}	4.6×10^{-8}	2.0×10^{-9}	4.6×10^{-10}
Ru-103	9.7×10^{7}	8.7×10^{7}	1.6×10^{-5}	1.2×10^{-4}	1.1×10^{-6}	1.2×10^{-6}	1.1×10^{-8}
Ru-106	6.7×10^{5}	6.6×10^{5}	2.0×10^{-6}	8.5×10^{-7}	8.4×10^{-9}	8.5×10^{-9}	8.4×10^{-11}
Cd-115m	1.0×10^{4}	9.5×10^{3}	1.5×10^{-5}	1.3×10^{-8}	1.2×10^{-10}	1.3×10^{-10}	1.2×10^{-12}
Sn-125	8.4×10^{5}	5.3×10^{5}	3.5×10^{-5}	1.1×10^{-6}	6.8×10^{-9}	1.1×10^{-8}	6.8×10^{-11}
I-131	1.7×10^{8}	1.0×10^{8}	1.6×10^{-3}	2.2×10^{-4}	1.3×10^{-6}	2.2×10^{-6}	1.3×10^{-8}
Cs-137	3.6×10^{5}	3.3×10^{5}	1.5×10^{-1}	4.6×10^{-7}	4.2×10^{-9}	4.6×10^{-9}	4.2×10^{-11}
Ba-140	3.1×10^{8}	2.2×10^{8}	6.0×10^{-4}	4.0×10^{-4}	2.8×10^{-6}	4.0×10^{-6}	2.8×10^{-8}
La-140	7.9×10^{7}	2.3×10^{8}	2.0×10^{-4}	1.0×10^{-4}	2.9×10^{-6}	1.0×10^{-6}	2.9×10^{-8}
Ce-141	1.5×10^{8}	1.4×10^{8}	9.0×10^{-4}	1.9×10^{-4}	1.8×10^{-6}	1.9×10^{-6}	1.8×10^{-8}
Ce-144	1.4×10^{10}	1.4×10^{7}	1.0×10^{-4}	1.8×10^{-2}	1.8×10^{-7}	1.8×10^{-4}	1.8×10^{-9}

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By considering concentration values at one week (10^4 minutes) and the larger initial diluting volume of Case B (100 m diameter x 10 m depth), the potential problem of ingestion of seafood from a contaminated water environment following the described water immersion accident seems not to create a problem of severe overexposure, even without the exercise of control in the offshore regions.

In the event of an accident occurring in the inland waterways, a different situation would prevail. No significant interchange between the waters of adjacent reaches of the Banana and Indian Rivers has been assumed. This restriction prevents any additional dilution beyond the uniform distribution in each reach as described in Section IV-E-3a.

By applying the diluting volumes as cited in Table IV-14 for the inland waterways to the nuclide activities in Table IV-15 for the ocean case, the same nuclides appear to be of significance. Due to the lack of any additional diffusion beyond the initial uniform distribution, a situation arises that would preclude the use of any particular reach of the waterway system for sport fishing unless countermeasures were applied. Activity levels in these inland water volumes would exceed MPCC values for times greater than one week, the limit of the WANL data.

F. SUMMARY

Three accident classes have been defined in this section for the purpose of delineating critical areas of concern on a preliminary basis:

1. The first accident class treats a release to the atmosphere from a $\sim 10^4$ MW-sec excursion unaccompanied by chemical energy release. All fission products except Zr, Nb, Mo, Tc, Ru. and Rh are assumed to be released at ground level. Prompt gamma and neutron doses would be fatal within about 200 meters of the unshielded reactor, dropping off to 0.5 rad at about 1,000 meters. Other doses are dependent upon meteorological conditions pertaining at the time of the accident. Under the most restrictive meteorological conditions treated, the whole-body gamma dose from cloud passage is less than 25 rad at 100 meters downwind;

the infinite gamma dose from surface contamination is 10 rads at 350 meters downwind; iodine inhalation dose to the thyroid is 300 rad at 600 meters downwind.

An accident of this magnitude occurring at Pad A should not produce significant injury to site workers. Off-site exposures appear to meet FRC Protection Guides with the exception of those deriving from iodine-contaminated milk which could create difficulties at distances greater than 50 miles (depending upon
not controlled.

2. The second accident class treats a nuclear excursion accompanied by a booster explosion. The nuclear energy release is assumed as $\sim 10^5$ MW-sec, with a release of all volatile elements and 10 percent of the beryllium and uranium as gaseous (or fine particulate) material, and a dispersion of the residual activity as fallout. It is shown that the assumed chemical energy release of 5×10^{11} calories from the equivalent of 10^6 pounds of H.E. produces a sufficient cloud rise to substantially eliminate external cloud gamma doses, or inhalation doses from fission products, uranium or beryllium as hazards. The fallout of larger particles (in the range of 100-1,000 μm), however, does present a substantial problem of beta burns to exposed skin surfaces. Surface dose rates from such particles one week after the accident would range from about 300 rad/hr for 75 μm particles to about 3,600 rad/hr for 6 mm particles.

3. The third accident class treats the injection of all fission products (except noble gases) from an excursion of $\sim 10^4$ MW-sec into the marine environment. It is shown that external dose from the contaminated water would not create exposure problems. Concentration of fission products in the coastal waters would be below permissible values after about one week. In the inland waters, substantial levels substantially undiminished by dispersion would persist, requiring control of the uses of such contaminated water volumes.

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V. REENTRY AND ULTIMATE DISPOSAL

Except for those missions which call for, and attain, orbital escape velocities, the ultimate disposition of the nuclear stage following mission completion will involve a return of the reactor to the surface of the earth. For orbital missions which follow programmed flight patterns, sufficient orbital decay time can be provided to eliminate problems from radiation upon return of reactor fragments to the earth. The initial flight tests (RIFT), however, will follow ballistic trajectories, and no substantial decay time will be available except for those fragments of the core which are sufficiently small to have a long residence time in the atmosphere.

Present plans call for the destruction of the reactor at high altitudes to permit burnup on reentry, and prevention of the return of excessive activity to populated areas of the earth. The design of a destruct system capable of fragmenting the reactor assembly into sufficiently fine particles has not been established at the present time; the system finally selected may incorporate conventional high explosives, chemical reaction with fuel elements, a violent nuclear excursion, or a combination of these.

Preliminary evaluations of reentry and ocean disposal hazards have been conducted by LASL,(93) Martin Company,(105) Vought Aeronautics,(106) USNRDL (107) and WANL.(108) In these studies, the preliminary conclusion has been reached that disposal to the deep ocean areas would not create a significant biological hazard. An evaluation of this aspect is made here using the approach outlined in Section III-B, and some assumptions of reactor history and reentry mode.

It is assumed that the reactor has operated for 30 minutes at 1120 MW, and that the fission product inventory corresponds to that produced by an instantaneous fission energy release of 2×10^6 MW-sec. It is further assumed that the core survives reentry in an essentially intact condition and undergoes an excursion of $\sim 10^5$ MW-sec on impact which fragments the core. No loss of volatile fission products during reentry or decay following reactor shutdown is assumed. This would result in fission product inventories ~ 200 times greater than those treated in the marine release accident in Section IV-E.

All volatile fission products (as defined in Table IV-8) are assumed to be released at the water surface, and transported downwind under arbitrarily selected neutral stability conditions with a 1.3 m/s wind. Residual fission products are assumed to be dispersed over an initial volume 100 meters in diameter and 100 meters deep. The radiological consequences of this reentry mode can be estimated by comparison with the results of the analyses performed in Section IV-C and IV-E.

Under these assumptions, at 1000 meters from the point of release whole body gamma dose would be about 450 rads, 380 rads from cloud passage, and about 70 rads from prompt radiation during the excursion. At 10,000 meters, (~6 miles) the cloud passage gamma dose would be less than 15 rad, and at 100,000 meters (~60 miles) less than 0.02 rad. Iodine inhalation doses (assuming no deposition) would be about 3.6×10^4 rad at 1000 meters, about 1000 rad at 10,000 meters, and about 13 rad at 100,000 meters. Iodine uptake via milk is difficult to estimate but under the assumption made might be significant (if uncontrolled)several hundred miles downwind of the release point. These values should be recognized as approximations, using diffusion parameters which may be inappropriate for overwater trajectories. Nevertheless, these values do serve to indicate the possible magnitude of downwind doses.

Release of non-volatiles to the water in accordance with the model described above is restricted to consideration of Zr, Nb, Mo, Tc, Ru and Rh. Additionally Ce, Y, and La from Group III of Table IV-8 will be considered as released to the water. The application of the diffusion model and MPCC values used in Section IV-E to this case results in the values shown in Table V-1. From these values, it can be noted that only Ru-103 and Ce-144 concentrations exceed MPCC 16 hours after the release, and that these drop rapidly to about two and four orders of magnitude below MPCC, respectively, at about one week after release.

On the basis of this preliminary estimate of hazard, it would appear that the ocean waters would not be adversely affected to a significant extent by residual fission product injection. The estimate of airborne contaminants yields doses which appear high, but it should be recognized that (1) the release of the volatile fission products (particularly noble gases and halogens) would very likely occur at high altitudes due to after-heat (decay heating) or reentry heating, rather than at the ocean surface, and (2) the complete release assumed to occur at the ocean surface neglects all consideration of possible entrapment mechanisms (in core material, water

TABLE V-1

SIGNIFICANT FISSION PRODUCT CONCENTRATIONS
IN THE OCEAN FOLLOWING REACTOR REENTRY

Nuclide	Activity, μc 10^3 Minutes	Activity, μc 10^4 Minutes	MPCC μc/kg	Peak Concentration μc/kg 10^3 Minutes	Peak Concentration μc/kg 10^4 Minutes
Y-91	3.4×10^9	4.6×10^9	7.0×10^{-2}	4.3×10^{-6}	5.9×10^{-8}
Zr-95	1.2×10^{10}	1.1×10^{10}	6.0×10^{-4}	1.5×10^{-5}	1.4×10^{-7}
Nb-95	3.0×10^7	6.8×10^8	5.0×10^{-3}	3.8×10^{-8}	8.7×10^{-9}
Ru-103	1.8×10^{10}	1.6×10^{10}	1.6×10^{-5}	2.3×10^{-5}	2.1×10^{-7}
Ru-106	1.3×10^8	1.3×10^8	2.0×10^{-6}	1.6×10^{-7}	1.6×10^{-9}
La-140	1.5×10^{10}	4.4×10^{10}	2.0×10^{-4}	1.9×10^{-5}	5.5×10^{-7}
Ce-141	2.9×10^{10}	2.7×10^{10}	9.0×10^{-4}	3.6×10^{-5}	3.4×10^{-7}
Ce-144	2.7×10^{12}	2.7×10^9	1.0×10^{-4}	3.4×10^{-3}	3.4×10^{-8}

spray, etc.). Although no basis is presently available for quantitative estimates of dose reduction by these mechanisms, it is felt that the doses developed above for airborne material from this fission energy release may be high by at least two orders of magnitude.

An alternative mode of reactor reentry involves the destruction and fragmentation of the reactor at very high altitudes, prior to reentry. On a gross basis the reentry of particles from a destroyed reactor would not create a significant hazard if the "fall-out" pattern follows that of high altitude weapons tests. However, the study by Fish and Patterson cited above,(54) does indicate that substantial doses to exposed body surfaces may result from single particles deposited on the skin or in passages of the respiratory tract.

This conclusion is supported by the dose calculations performed in Section IV-D above. The assumption is made that the beta power level (and the resulting particle surface dose) is directly proportional to the integrated reactor power. The reactor operating history is assumed to be 30 minutes at 1120 MW (or 2×10^6 MW-sec), or ~20 times the integrated power treated in Section IV-D. If a further assumption is made that the beta energy spectra are similar in both cases, then the beta dose rates at the surface of the reentering particles would be some 20 times those indicated in Figure IV-29.

Typical surface dose rates derived on this basis are listed in Table V-2 for particle sizes at the earth's surface. Implicit in this presentation is the assumption that no fractionation of fission products occurs following operation, either during after-heat, destruct or ablation periods. The concentration per unit mass is assumed to remain the same (except for decay) and is not affected by the loss in particle mass during reentry.

From this table it may be noted that the skin dose rates would be quite high from single particles as small as 25 - 50 μm in diameter at the earth's surface. It seems apparent that, although the gamma dose from a widely dispersed pattern of particles may not create a significant hazard, single fine particulates in contact with the skin or other more sensitive tissues could deliver highly significant beta doses.

If the destruct system is to function so as to prevent hazard to individuals, it would require an initial particle size distribution with an extremely small

TABLE V-2

BETA DOSE RATES AT THE SURFACES OF SPHERICAL, REENTERED PARTICLES

Estimated Initial Particle Diameter, μm	Final Particle Diameter, μm	Approximate Settling Time,* Minutes	Beta Dose Rate at $t = 10^4$ min, rads/hr.
~1200	1000	67	5.2×10^4
~1000	600	100	4×10^4
~ 400	200	330	1.8×10^4
~ 270	100	970	1.0×10^4
~ 225	75	1300	6.7×10^3
~ 150	50	2500	4.2×10^3
~ 75	25	11700	2.2×10^3

* From 100,000 feet.

maximum value -- much less than 100μm. If a system, or combination of systems, cannot guarantee such a size distribution, serious consideration should be given to directed reentry of the intact nuclear engine into deep ocean areas. Although an excursion would almost certainly occur on impact, the released material would be dispersed and diluted either in the atmosphere or the ocean with a very high probability of negligible exposure to humans if the disposal area is selected with care. An alternative approach would be the fragmentation of the core into subcritical portions at a relatively low altitude. This would prevent the excursion on impact, and tend to confine the fallout to a relatively small area.

VI. RADIATION PROTECTION STANDARDS

A. GENERAL

1. Origin and Status of Standards

Some of the major organizations which establish radiation protection standards are:

a. International Commission on Radiological Protection (ICRP).
b. National Committee on Radiation Protection and Measurements (NCRP) - USA.
c. Federal Radiation Council (FRC) - USA.
d. Atomic Energy Commission (AEC) - USA.

Standards of the first two organizations listed above are in the form of recommendations; those of the latter two are law.

There are many other activities which establish radiation protection standards. They are not mentioned here in order not to further complicate the subject matter.

The basic principles of all radiation protection standards, in general, originate with the ICRP. In turn, the NCRP adapts the ICRP recommendations so that they are more applicable to our national characteristics and requirements. The Federal Radiation Council, which was formed by Public Law in 1959 to establish Federal policy in human radiation exposure, published its first set of radiation protection standards [109] in May, 1960. The FRC recommended standards were approved by the President for the guidance of Federal agencies. The other major agency which establishes legally-binding standards is the AEC. Presently, there are two AEC standards: One [110] applicable to AEC contractors and AEC activities and the other [111] to licensees of the AEC. Standards applicable to weapons tests in Nevada or the Pacific Proving Ground are the subject of a separate authorization.

All of the various standards, in general, are in rather close agreement. This is to be expected, as the radiation protection experts who represent the USA on the ICRP are directly or indirectly serving in the activities which establish national standards.

2. Types of Standards

a. Situation

Peacetime radiation protection standards can be broadly divided into two general types: (1) normal operations and (2) emergency conditions. There also exist recommended standards for non-peacetime conditions in which the main problem is the survival of the individuals exposed, rather than estabilshment of "acceptable" doses.

b. Classification of Persons

In a set of standards there are different limits for: (1) the radiation workers (occupational exposure) and (2) the general population. The ICRP also includes an intermediate special group consisting of the following: adults who work in the vicinity of controlled areas, but who are not radiation workers; adults who enter controlled areas occasionally in the course of their duties, but who are not radiation workers; and members of the public living in the neighborhood of controlled areas.

c. Types of Exposures

Standards are established for the two types of radiation exposures: external and internal. External radiation exposure is that exposure which results from radiation sources which are located outside the body. Internal radiation exposure is that which results from radioactive materials which are within the body.

d. Body Organs

In a set of standards, different exposure limits are specified for the following groups of body organs: (1) whole body, head and trunk, active blood-forming organs, gonads, or lens of eye; (2) skin of whole body, and thyroid; (3) hands and forearms, feet and ankles; (4) bone; and (5) other organs.

e. Additivity of Exposures

When external exposure and internal exposure are concurrent, the limits specified in a particular set of standards should be

reduced appropriately. If external exposure occurs at "A" percent and internal exposure at "B" percent of their respective separate limits, then the combined exposure is considered acceptable if A + B does not exceed 100. The same principle applies if there is a concurrent internal exposure from several radionuclides, with or witnout concurrent external exposure. When the radionuclides in a mixture are taken up by several body organs and the resultant tissue doses in such organs are of comparable magnitude, the combined exposure is considered to constitute essentially a whole-body exposure. Accordingly, the permissible dose of exposure will be that applicable to the whole body. There are no definitive standards concerning the additivity of individual body organ (thyroid, hands and feet, etc.) doses so as to combine them as a single risk factor. The NCRP, however, has this problem under consideration.

B. STANDARDS FOR NORMAL PEACETIME OPERATIONS

All of the four activities listed above have established radiation protection standards for both radiation workers and the population, for continuous exposure in normal peacetime operations. The standards of all four activities are essentially in agreement.

The FRC Radiation Protection Guides [109] for normal operations are contained in Table VI-1. FRC's Guides [50] applicable to normal operations and designed to limit internal exposure of population groups to radiations from Radium-226, Iodine-131, Strontium-90, and Strontium-39 are contained in Tables VI-2, VI-3, and VI-4.

The AEC standards, 10 CFR 20,[111] which are applicable to its licensees, are the same as those of the FRC, on a yearly basis. On a quarterly-year basis, the AEC standards for radiation workers are more restrictive than those of the FRC. The AEC-specified limits for external exposure of radiation workers are listed in Table VI-5. In accordance with 10 CFR 20, dose rates in unrestricted areas (areas outside the control of the licensee) must be such that an individual who is continuously present in the area could not receive a dose in excess of 2 millirems in any one hour, or a dose in excess of 100 millirems in any seven consecutive days. The AEC will approve higher dose rates, provided the licensee furnishes proof that the proposed limits are not likely to cause an off-site individual to receive a whole-body dose in excess of 0.5 rem in any one calendar year.

TABLE VI-1

FRC RADIATION PROTECTION GUIDES FOR NORMAL PEACETIME OPERATIONS

Type of Exposure	Condition	Dose (rem)
Radiation Worker:		
(1) Whole body, head and trunk, active blood-forming organs, gonads, or lens of eye	Accumulated dose ---	5 times the number of years beyond age 18
	13 Weeks -----	3
(2) Skin of whole body and thyroid	Year ----------	30
	13 Weeks -----	10
(3) Hands and forearms, feet and ankles	Year ----------	75
	13 Weeks -----	25
(4) Bone	Body Burden ----	0.1 microgram of radium-226 or its biological equivalent
(5) Other Organs	Year ----------	15
	13 Weeks -----	5
Population:		
(1) Individual	Year ----------	0.5 (whole body)
(2) Average	30 Years ------	5 (gonads)

Note: For the individual in the population, the basic Guide for annual whole-body dose is 0.5 rem. This Guide applies when the individual whole-body doses are known. As an operational technique, where the individual whole-body doses are not known, a suitable sample of the exposed population should be developed whose protection guide for annual whole-body dose will be 0.17 rem per capita per year. It is emphasized that this is an operational technique which should be modified to meet special situations.

TABLE VI-2

FRC RADIATION PROTECTION GUIDES FOR CERTAIN BODY ORGANS IN RELATION TO EXPOSURE OF POPULATION GROUPS - NORMAL PEACETIME OPERATIONS

Organ	RPG for Individuals	RPG for Average of Suitable Sample of Exposed Population Group
Thyroid	1.5 rem per year	0.5 rem per year
Bone marrow	0.5 rem per year	0.17 rem per year
Bone	1.5 rem per year	0.5 rem per year
Bone (alternate guide)	0.003 micrograms of Ra-226 in the adult skeleton or the biological equivalent of this amount of Ra-226.	0.001 micrograms of Ra-226 in the adult skeleton or the biological equivalent of this amount of Ra-226.

TABLE VI-3

FRC GRADED SCALE OF ACTIONS

Ranges of Transient Rates of Daily Intake	Graded Scale of Action
Range I	Periodic confirmatory surveillance as necessary.
Range II	Quantitative surveillance and routine control.
Range III	Evaluation and application of additional control measures as necessary.

TABLE VI-4

FRC RANGES OF TRANSIENT RATES OF INTAKE (MICROCURIES PER DAY) FOR USE IN GRADED SCALE OF ACTIONS SUMMARIZED IN TABLE VI-3 - NORMAL PEACETIME OPERATIONS

Radionuclides	Range I	Range II	Range III
Radium-226	0-2	2-20	20-200
Iodine-131 (1)	0-10	10-100	100-1,000
Stontium-90	0-20	20-200	200-2,000
Strontium-89	0-200	200-2,000	2,000-20,000

(1) In the case of Iodine-131, the suitable sample would include only small children. For adults, the RPG for the thyroid would not be exceeded by rates of intake higher by a factor of 10 than those applicable to small children.

TABLE VI-5

AEC RADIATION PROTECTION GUIDES FOR OCCUPATIONAL EXPOSURE

Rems per Calendar Quarter

1. Whole body; head and trunk; active blood-forming organs; lens of eyes; or gonads	1 1/4 rems
2. Hands and forearms; feet and ankles	18 3/4 rems
3. Skin of whole body	7 1/2 rems

Note: A licensee may permit an individual radiation worker to receive a dose not to exceed 3 rems in any calendar quarter, provided that the accumulated dose for that individual does not exceed 5 (N-18) rems, where "N" is the individual's age in years, and the licensee has determined proof of this in an AEC-specified record form or its equivalent.

The ICRP (112) has recommended that the genetic dose to the whole population from all sources additional to the natural background should not exceed 5 rems plus the lowest practicable contribution from medical exposure. The genetic dose is considered to be accumulated during a period of thirty years. Furthermore, the ICRP suggests that this genetic dose limit not be used by one single type of exposure and recommends the following apportionment for guidance purposes:

1. Occupational exposure	1.0 rem
2. Exposure of special groups	0.5 rem
3. Exposure of the population at large	2.0 rems
4. Reserve	1.5 rems
TOTAL	5.0 rems

The genetic dose limit of 2.0 rems/30 years for the population at large (with the 1.5 rems for possible eventualities) is intended for planning purposes in the development of nuclear energy problems and more extensive use of radioactive materials. It was further suggested that of the 2.0 rem genetic dose limit, 1.5 rems be the limit for internal dose and 0.5 rem for external dose. For internal exposure when the total body or gonads is the critical organ, this limit of 1.5 rems/30 years means a reduction factor of 0.01 is to be applied to the maximum permissible concentrations established for continuous (168-hour week) occupational exposures to radioactively contaminated air and water used by the population at large.

C. STANDARDS FOR PEACETIME EMERGENCIES

1. ICRP

The following recommendations, applicable to radiation workers, have been made by the ICRP:

a. One or more short-term internal exposures to radioactive materials (together with any external exposure) within a period of thirteen consecutive weeks is considered acceptable if the total intake of radioactive material during this period does not exceed the amount that would result from intake for thirteen weeks at the maximum levels for occupational exposure to such radioactive materials permitted by the 1959 Report of Committee II. (45)

b. Emergency work involving internal exposure above permissible limits to radioactive materials shall be planned on the basis that the total intake of radioactive material during the emergency period should not exceed the amount that would result from intake for one year at the maximum levels for occupational exposure to such radioactive materials permitted by the 1959 Report of Committee II.[45] The dose to the critical organs during the following fifty years resulting from such an intake will not exceed the 1958 ICRP-recommended limits: (1) 12 rems for whole body and gonads; (2) 30 rems for skin, thyroid, and bone; and (3) 15 rems for other organs.

The subject of emergency exposure of environmental populations was discussed extensively during the 1959 Zurich meetings of the ICRP. The ICRP considered that the British Medical Research Council (BMRC) Report[113] recommending criteria for acceptable levels, under emergency conditions, of Iodine-131, Strontium-89, Strontium-90, and Cesium-137 ingested in food or milk, constitutes a useful and sound approach to the subject.[114] The ICRP itself, however, has not recommended any emergency limits for environmental populations.

2. NCRP

The NCRP has recommended the following emergency dose limit for radiation workers: An accidental or emergency dose of 25 rems to the whole body or a major portion thereof, occurring only once in the lifetime of the person, need not be included in the determination of the radiation exposure status of that person.[115]

The NCRP has not recommended any peacetime emergency standards applicable to the general population. However, in its Report No. 29,[102] the NCRP makes recommendations concerning a radiation emergency, which it defines as "an accident, or other event out of the ordinary, that threatens to expose people to more than 25 rems in one week." In this same report the NCRP states: "It is expected that most radiation accidents in peacetime can be handled satisfactorily under the principles set forth in Handbook 59."

3. FRC

To date, the FRC has established standards which are applicable only to normal peacetime operations.

4. AEC

The AEC radiation protection standards do not contain any emergency exposure limits, as such, for either radiation worker or the general population. However, one may infer degrees of seriousness of a radiation incident from the criteria specified for two types of incidents which are reportable to the AEC.[111] An AEC licensee is required to notify immediately the AEC whenever an incident results in any individual receiving a whole body dose of 25 rems or more, or whenever radioactive material is released in concentrations (averaged over a 24-hour period) which exceed 5,000 times the specified limits for such materials. The other reportable incident, which requires notification of the AEC within 24 hours, is one which results in an individual receiving 5 rems (whole body) or more, or if the concentration of released radioactive material (averaged over a period of 24 hours) exceeds 500 times the limits specified for such materials.

Another source of guidance to AEC inferences on severity of radiation emergencies derives from the AEC's 10 CFR 100 (Reactor Site Criteria)[116] which is intended to assure that the cumulative exposure dose to large numbers of people as a consequence of any nuclear accident should be low in comparison with what might be considered reasonable for total population dose. Following are criteria contained in 10 CFR 100:

a. An exclusion area of such size that an individual located at any point on its boundary for two hours immediately following onset of the postulated fission product release would not receive a total radiation dose to the whole body in excess of 25 rem or a total radiation dose in excess of 300 rem to the thyroid from iodine exposure.

b. A low population zone of such size that an individual located at any point on its outer boundary who is exposed to the radioactive cloud resulting from the postulated fission product release (during the entire period of its passage) would not receive a total radiation dose to the whole body in excess of 25 rem or a total radiation dose in excess of 300 rem to the thyroid from iodine exposure.

c. A population center distance of at least one and one-third times the distance from the reactor to the outer boundary of the low population zone. Population center distance means the distance from the reactor to the nearest boundary of a densely populated center containing more than about 25,000 residents. In applying this guide, due consideration should be given to the population distribution within the population center. Where very large cities are involved, a greater distance may be necessary because of total integrated population dose consideration.

The whole-body dose of 25 rems corresponds numerically to the "once in a lifetime" accidental or emergency dose for radiation workers which, according to NCRP recommendations, may be disregarded in the determination of the radiation exposure status. However, neither its use nor that of the 300 rem value for thyroid exposure as set forth in 10 CFR 100 are intended to imply that these numbers constitute acceptable limits for emergency doses to the public under accident conditions. Rather, this 25 rem whole-body value and the 300 rem thyroid value have been set forth in these guides as reference values, which can be used in the evaluation of reactor sites with respect to potential reactor accidents of exceedingly low probability of occurrence, and low risk of public exposure to radiation.

5. <u>British Medical Research Council</u>

As stated earlier, the ICRP considers that the British Report,(113) concerning standards for dietary contamination during a radiation emergency, constitutes a useful and sound approach to the subject. The basic criteria used by BMRC is that the total doses, resulting from levels of intake continued during the course of the contamination, are about equal to the ICRP-recommended, occupational, annual maximum permissible doses (MPD) for the tissues involved:

Radionuclide	Accumulated MPD (rad) BMRC	Annual MPD (rad) for Radiation Workers - ICRP
Iodine-131	25 (thyroid)	30
Strontium-89	15 (total)	15
Strontium-90	1.5 (annual rate)	15
Cesium-137	10 (whole body)	12 (max); 5 (average)

The BMRC-recommended limits are on the basis that the number of persons exposed will be small compared with one-fiftieth of the whole population of the United Kingdom. Also taken into consideration was the possibility, however unlikely, that the same persons might be significantly exposed to a second accidental release of radioactive materials. The BMRC-recommended limits for dietary intake during an emergency condition are listed in Table VI-6. These values were computed on the basis of the accumulated MPD values tabulated above. The difference in intake limits for the specified age group is due to their differences in pertinent biological factors.

The BMRC report regards milk as the most significant source of Iodine-131. For children fed on liquid milk only, the maximum thyroid irradiation would likely occur at an age of about 6 months, since the thyroid increases very little from birth until this age, whereas the milk intake may increase with body weight until this age. The recommended intake level of 60 mμc/day corresponds to a peak Iodine-131 concentration in milk of 0.065 μc/liter, assuming milk intake of 0.9 liters/day at the age of 6 months.

A later report(117) from the British Medical Research Council deals with exposure from radioactive material which is inhaled during passage of a cloud of radioactive material. Inhalation radiation hazards would be of most concern to persons working or living in the immediate environs of the site of the radiation accident. Such persons would also be exposed simultaneously to external radiation of relatively short duration during the passage of the same cloud and subsequently also to external radiation from material deposited from the cloud and to internal radiation from the affected foodstuffs. Consequently, doses received from inhalation of radionuclides will determine the acceptable amount of radiation from the other sources

TABLE VI-6

BMRC EMERGENCY DIETARY INTAKE LIMITS [113]

Iodine-131

Age Group	Initial Daily Intake (mμc)	Total Intake (mμc)
To age 6 months	60	650
3 years	110	1,200
10 years	300	3,400
Over 20 years	1,300	15,000

Cesium-137

Age Group	Daily Intake (mμc)	Total Intake (μc)
At birth	60	6
6 months	150	15
Over 20 years	1,150	115

Radiostrontium:*	Daily Intake (mμc) - for any age
Strontium-89	200
Strontium-90	2

*Note: When both strontium radionuclides are present, the level of each should be reduced accordingly.

mentioned. In determining the recommended maximum permissible contamination values for respirable air after an accidental release of radioactive material, the BMRC used the same basic criteria for total doses (25 rems to thyroid, 10 rems to total body, etc.) as it used for the emergency dietary contamination limits. In addition, the Council used for the inhalation problem a maximum total dose of 15 rads to the lungs. As in the dietary case, BMRC also took into account the small probability that the same persons would be involved in more than one emergency. In the opinion of the Council, the limits have been set sufficiently low that a second emergency exposure after a period of some years should not give rise to undue concern. The BMRC-recommended maximum permissible total intakes and time integrals of the concentrations in air, following a nuclear reactor accident are listed in Table VI-7.

The BMRC-recommended intake limits may be compared with the values derived from the ICRP recommendation for emergency exposure of radiation workers - that "the total intake of radioactive materials during the emergency period should not exceed the amount that would result from intake for one year at the maximum permissible levels for occupational exposure to such radioactive materials permitted by the 1959 report of Committee II." These ICRP-derived values, which are included in Table VI-7 for comparison purposes, are very similar to the BMRC-recommended total intake limits.

Concerning internal exposures, it is to be noted that, when more than one radionuclide irradiates the same organ, the doses they contribute are additive. Intake of Cesium-137, for which the whole body is the critical organ, automatically reduces the permissible intake of all other radionuclides.

The BMRC-recommended maximum permissible time integrals of the concentrations in Table VI-7, are computed by using the appropriate physiological factors (breathing rates, uptake, etc.) for the different age groups.

The BMRC report gives the following as the average dose to the lungs resulting from the recommended total intake limits specified in Table VI-7. In deriving these figures, the BMRC assumed the radionuclides to be in an insoluble form. This is the worse case, as the lung dose increases with the degree of insolubility of the particulate radioactive material.

TABLE VI-7

BMRC MAXIMUM PERMISSIBLE INTAKE LIMITS(117)

Radionuclide	Age of Person	Total Intake (μc)	Time Integral of Concentration (mμc - hour/liter)
Iodine-131*	At Birth	0.88	8.8
	6 Months	0.88	3.5
	1 Year	1.1	3.3
	Adult	20 (ICRP: 22μc)	24
Strontium-89	At Birth	2.8	28
	6 Months	5.5	22
	1 Year	8.3	25
	Adult	83 (ICRP: 75μc)	100
Strontium-90	At Birth	0.028	0.28
	6 Months	0.057	0.23
	1 Year	0.085	0.26
	Adult	0.85 (ICRP: 0.75μc)	1
Cesium-137	At Birth	8	80
	6 Months	19	76
	1 Year	22	66
	Adult	150 (ICRP: 150 μc)	180

*Where there is a contribution from other radioiodines and Te-132, the values given for Iodine-131 should be reduced by a factor of two. In certain rare circumstances (shortly after criticality), the values might have to be reduced by a factor of ten.

Age of Person	Lung Dose (rads) I-131	Sr-89	Sr-90	Cs-137
Birth	0.37	10	0.67	70
6 Months	0.17	9	0.62	78
1 Year	0.16	11	0.73	71
Adult	0.42	15	1.00	67

These figures indicate that the BMRC total intake limits for Iodine-131, Strontium-89, and Strontium-90 will not result in a lung dose exceeding the BMRC-recommended emergency limit of 15 rads. The much larger computed values for the case of Cesium-137 are not considered significant because the probability of Cesium-137 appearing in an insoluble form is so low as to make it extremely unlikely. The BMRC report did not indicate the lung dose values for Cesium-137 in the soluble form.

6. Additional Comments

Dunning[118] has stated that, although the thyroid dose resulting from ingesting fallout may be greater than the dose to the G. I. tract, the greater sensitivity of the G. I. tract may make it a controlling consideration in selecting emergency exposure levels. In the BMRC reports,[113,117] no mention was made of the G. I. tract doses which would result from ingestion or inhalation at the recommended emergency limits.

Horton[119] has computed guides for radioiodine concentrations in the various foodstuffs comprising basic diets of various categories of people (different ages and both sexes). The criteria used for an acute emergency exposure was a thyroid dose of 25 rems (to only the limiting category of people), which is the same as the value used in the BMRC reports[113,117] Horton's article contains a table of RCG (Radioactivity Concentration Guides) values for Iodine-131, Iodine-132, Iodine-133 and Iodine-135 in the various types of foodstuffs comprising a representative diet. The RCG for milk is given as 1.4×10^{-4} μc/ml (as compared to BMRC's value of 0.65×10^{-4} μc/ml) and for eggs as 1.6×10^{-1} μc/egg. Horton did not mention the G. I. tract dose which would result from intake of the foodstuffs contaminated at the recommended

RCG values. It may be of interest to compare intake rates computed from Horton's RCG values with those recommended by the BMRC. Horton's RCG value for Iodine-131 in milk in 1.4×10^{-4} μc/cc. According to his food consumption figures, the weekly consumption of milk by children (9 months to 2 years) is 5.680 cc - which would result in a weekly Iodine-131 intake of 0.8 μc, or an average daily intake of 114 mμc. The BMRC daily intake limits are 60 mμc for age up to 6 months and 110 mμc for 3-year-old children.

It may be of interest here to state that the Windscale accident showed that eggs are the greatest source of Iodine-131, next to milk.[120] Experiments with laying hens, to which Iodine-131 had been administered orally, indicated that their eggs contained about 8 to 9 percent of the daily administered dose - steady state having been reached in about 7 days. The yolk contained the major portion of the Iodine-131; very little activity was found in the albumin and shell.

Morgan, Snyder, and Ford[121] have reported a calculation method for estimating the maximum permissible intake (MPI) of radionuclides for a single exposure. Many radioactive materials are relatively insoluble, and the fraction entering the blood stream following ingestion or inhalation is small, so that the gastrointestinal (GI) tract becomes the critical body tissue rather than the kidney, bone, or other body organ. Of the 355 maximum permissible concentration (MPC) values listed in the ICRP Handbook (ICRP/54/4 - 1954), 71 percent of those for ingestion and 41 percent of those for inhalation refer to the G. I. tract as the critical organ. This means that the G. I. tract receives the maximum permissible dose rate of 0.3 rem/week at a lower MPC value than that for any other body organ. The lung is another body organ which is likely to receive a high exposure, and consequently becomes the critical organ, as a result of a single exposure. For short-period exposures, the lung is the critical body organ for about 50 percent of the radionuclides when the permissible dose is set at a limit of 0.3 rem during the week following the exposure, and for 83 percent of the radionuclides when the permissible dose is set as 0.3×52 or 15.7 rem during the ensuing year. In most of the other cases, the G. I. tract is the critical organ.

Cowan and Kuper[122] defined the AED (Acceptable Emergency Dose) unit for a catastrophic accident as 25 rems of whole-body gamma exposure or its equivalent of other types of exposure. There is not firm basis for converting lung dose (principally due to beta radiation) to equivalent whole-body gamma dose. However, on the basis that NCRP permitted five times as much beta exposure to the skin as gamma, and also permitted five times as much exposure to the extremities as to the whole body, the authors felt it was conservative to use a factor of five in reducing lung exposures to whole body equivalents. Concerning Strontium-90, one μc deposited in the bone was taken as one AED, which on the basis of the physiological factors used, corresponded to an inhalation intake of 10 μc. Seventy-seven times as much inhaled Strontium-89 as Strontium-90 would correspond to one AED, or 770 μc. Inhalation of 203 μc of Cesium-144 was taken as corresponding to one AED. For thyroid irradiation due to radioiodines, the AED was set at one-tenth of the lowest figure at which symptoms may be expected, or 2,000 rads to the gland. A value of 400 μc of radioiodine in the thyroid, as of t = 24 hours, was estimated to result in this dose. On the basis of the physiological factors used, an inhalation intake of 2,660 μc of radioiodine corresponded to one AED. A single dose of 50 rad to the G. I. tract was considered one AED.

In determining the total direct exposure in the case of limits for "no injury," the authors considered it conservative simply to add up the partial exposures as expressed in AED units. Indirect exposure due to deposition of fission products was also considered, and limits were suggested for evacuation and varying degrees of restriction on the use of the contaminated land. The five situations recognized for indirect exposure were: (1) urgent evacuation (within 12 hours); (2) evacuation necessary; (3) severe restrictions on land use, possible temporary evacuation, restrictions on outdoor work; (4) probable destruction of standing crops, restrictions on agriculture for first year; and (5) no exposure likely. It was recommended that a dose rate which would result in a 24 rem dose being received in the first 12 hours would appear to call for urgent evacuation.

D. SUMMARY AND DISCUSSION

1. The primary assumption on which radiation protection standards are based is that all exposures, however small, have an associated

risk of harmful biological effects. A second assumption is that the risk of harmful biological effects from small doses of radiation increases with the cumulative dose. These assumptions lead to a requirement that exposure to radiation be accepted when, and only when, the reasons for acceptance are believed to balance the risk of biological damage. (123)

2. For normal peacetime operations, the FRC Radiation Protection Guides, presented in Table VI-1, contain currently accepted standards. There are presently no established national legal standards for peacetime radiation emergencies involving a portion of the general public. The only available numerical values for such situations are the 25 rem whole-body dose and the 300 rem thyroid dose stated in the AEC's 10 CFR 100 for reactor site criteria. These figures, however, are not considered as standards. The 25 rem whole-body dose is the "once-in-a-lifetime" emergency dose considered as allowable for radiation workers by the NCRP, and is a numerical value which seems to have wide acceptance. The recommended emergency exposure values of the British Medical Research Council (namely; 10 rems to the bones or lung) for off-site persons are significantly lower than the corresponding reference values in 10 CFR 100. The approach taken by the BMRC in arriving at its recommended limits is considered to be a useful and sound one by the ICRP. In addition, the BMRC took into account the probability, however remote, that the persons exposed during one emergency may possibly be exposed as a consequence of a second one.

3. The establishment of radiation protection standards for the nuclear space program is a function which must be exercised by the appropriate government agency. As indicated by the creation of the Federal Radiation Council, the establishment of such standards requires not only a consideration of biological effects, but also a judgment with regard to the benefit-risk relationship.

The evaluation of risk to off-site individuals made in this report has been based to a considerable extent upon the recommendations of the FRC for continuous exposure of the general public. The evaluation has shown that, with the exception of Iodine-131 in milk, no substantial departure from these standards should occur for accidents in the vicinity of Complex 39. In the case of iodine in milk, concentrations might exceed FRC-based guides by factors

of from 10 (dry) to 20 (wet) and resulting in doses of from 15 to 30 rem to a child's thyroid, values within the range of the BMRC recommendation and well below the AEC site criteria planning guidance.

For the on-site worker, the applicable standards are less clear, primarily due to the question of the status of those employees not directly associated with the nuclear programs at Cape Canaveral. If they are assumed to be radiation workers in the sense that they are amenable to control in the event of an incident, and that a recognition of this risk is implicit in their employment, then occupational radiation exposure limits would apply. If this assumption is tenable, then the evaluation indicates no substantial difficulties introduced by accidents at or near the launch pad, with both whole-body and thyroid doses within annual exposure limits.

Accidents within the assembly area which are not totally or partially alleviated by containment or shielding could result in fatalities and serious injuries to workers in the immediate vicinity, and attention given to prevention of such occurrences is highly desirable.

In the absence of radiation protection guidance by appropriate Federal agencies, NUS would recommend the use of FRC guidance for off-site residents, and the BMRC emergency guides for on-site workers, for interim evaluation of accidental radiation exposures.

VII. EVALUATION OF ANALYTICAL MODEL

A. SOURCES OF ERROR AND UNCERTAINTY

It is obvious from a consideration of the number of assumptions made in the course of this hazard evaluation that there are numerous sources of error and uncertainty in the doses derived for the various accident cases considered. These sources of error or uncertainty arise both in the definition of the source and in the transport of material. The uncertainty in response of a biological system (such as man) to a given insult from radiation is not considered in this study.

There are several types of errors and uncertainties which may be considered to occur in this analysis. The first is that due to the inability of a mathematical model to represent faithfully a particular system. This is the type of uncertainty that is assigned to the use, for example, of the Pasquill or Sutton equations to describe a complex atmospheric system affected by many factors and parameters which are not included except on a gross basis in the formulations. Another example of this is the inexactness of the RAC formulation for describing the kinetics of the reactor core and the behavior of the core materials. In each of these cases the formulations and the parameters which are used are the best which can be employed at the present time to describe highly complex occurrences and it is recognized that, in both cases, answers supplied by the calculation will only approximate the physical reality which they attempt to represent.

The other type of uncertainty is that which derives from the inability to define in advance the conditions which will prevail at the time of an accidental occurrence. Since an accident is by definition an unplanned or unforeseen event, it is impossible to do more than speculate with respect to the states of both the environment and the system under consideration during the course of and immediately following an accident. If one could with certainty describe the chronology of events taking place before the occurrence, then such events would be precluded by changes in circumstances vital to the chronology.

Since the circumstances of an accident are unknown, an analysis of this type should indicate the effect of changes in significant variables upon the resulting hazards. Quite frequently the worst conceivable circumstances are chosen with the expectation that there are no set of circumstances which will give a worse effect. Thus, it is typical to consider the coincidence of the "maximum credible accident" in a conventional

nuclear reactor occurring at a time when weather conditions are least favorable, with the further restriction that dose exposures all occur at the worst possible location (i.e., the cloud centerline or the site boundary) for an infinite or at least indefinite time.

The discussion that follows attempts to indicate those sources of error and uncertainty in both the source and environment which would have a significant effect upon the resulting hazard for a given circumstance. It also attempts to indicate the latitude that may exist, either by present lack of knowledge of system characteristics or through the inability to predict the circumstances at the time of an accident.

1. Source Definition

Definition of the source term and its significance in the hazard evaluation cannot be underestimated with respect to its importance. This study has attempted to indicate that a significant description of the source term includes more than the number of fissions which occur and an indication of the gross fission product percentage which escapes the core. Also required is a detailed indication of the specific fractionation of fission products as between volatile and non-volatile elements, the physical and chemical state of the fission product and toxic materials at the time of release (whether gaseous or solid, and if solid with respect to particle size distribution), and other significant factors such as the initial spatial distribution, geographic location, the time of release, and the amount of thermal and kinetic energy associated with the source. Each of these is described in some detail in the succeeding sections.

a. Location

The location of an accident is highly significant in terms of delivered dose, since the separation distance between source and receptor is obviously a major factor in dose reduction. Yet the location of an accident beforehand is essentially impossible to specify. This study has assumed that the accidents on dry land releasing radioactive material to the atmosphere took place at Launch Pad A. Figure IV-27 indicates the limits for location of accidents which would not result in doses higher than those specified on the figure at the assembly buildings of Complex 39. It is not inconceivable, however, that accidents could occur at closer locations than those specified in the figure. For example, it is conceivable, that a vehicle enroute to the launch pad might topple into the waters of Banana Creek, lying between the assembly area and the launch pads, due to the occurrence of a line squall which may occur in the Florida area with little or no warning.

The location of impact point for booster failure accidents are considerably more difficult to define. Figure VII-1 indicates the impact points of liquid fueled vehicles which have impacted within six miles of their launch site(85), transposed to the launch site (Pad A) and flight path (100^{o}) proposed for NERVA - RIFT. A circle of about three-mile radius centered two miles down the flight path somewhat generously encompasses all of the plotted impact points. If the circumference of the circle is assumed to be a reasonable limit line for vehicle abort impact points, then at the point of closest approach, the perimeter of the circle would be less than a mile from the vertical assembly building. The effects in the assembly area and on the mainland would be considerably different in this case than they would if the impact point were six miles away, off-shore.

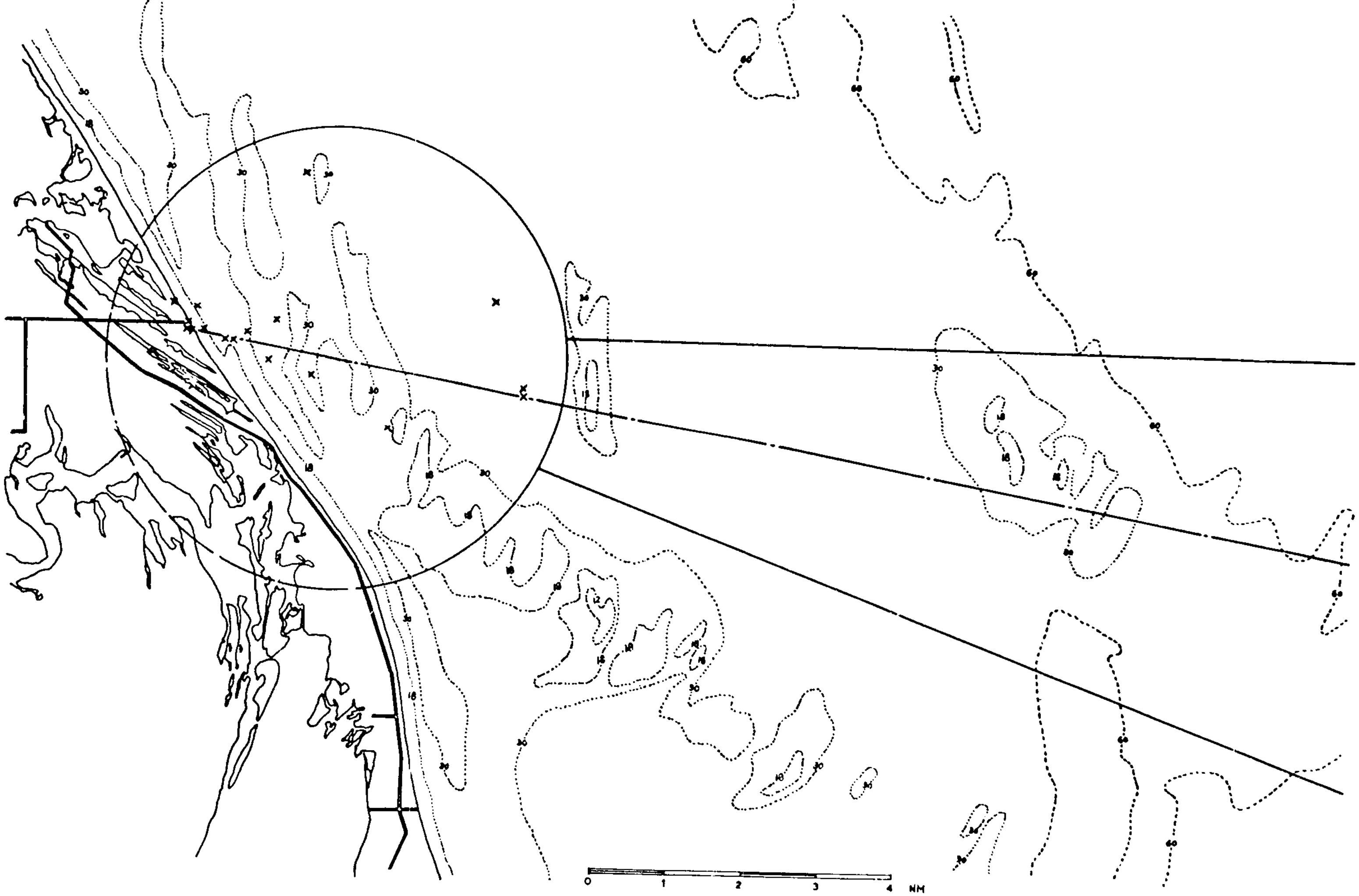
In addition to the geometrical relationship of source and receptor, the location of an impact of this type would also be highly significant with respect to the presence or absence of water and the degree of energy release that might occur. Since the actual location of an accident is not predictable and the consequences appear to be highly variable with location, it is not possible to assess the magnitude of the error caused by assuming the location at Launch Pad A.

b. Magnitude - RAC Excursions

The more important assumptions intrinsic in the RAC formulation are worthy of consideration. Appendix A describes in some detail the calculational formalism employed in RAC to compute fission yields from various prompt excursions. Briefly, the generation of fission energy, the equations of motion, etc., are integrated step-wise in space and time throughout the history of the burst. The comments below are addressed both to the reactor kinetics assumptions of the code and the materials assumptions of the graphite-urania fuel system employed in the code.

(1) Reactivity compensation can occur only through axial expansion of the core. It is clear from the axial power

FIGURE VII-1



IMPACT POINTS OF LIQUID-FUELED VEHICLES TRANSPOSED TO LAUNCH PAD A(85) distribution of Figure VII-2 that the axial distribution is essentially independent of radial position. It is not clear that the converse is true -- that the radial distribution of Figure VII-3 is independent of axial location, particularly at inlet and outlet plenums or with end-flooding. Radial and axial expansion occur in the actual system with large insertions of reactivity; the omission of the radial contribution as an additional compensation mechanism may penalize the design unduly.

(2) The neglect of lessened neutron leakage from an (axially) expanded core in the RAC kinetics is probably not significant, partly due to a compensating increase in the leakage neutron age, so that the fast non-leakage term $(1 + \tau B^2)$ would remain relatively constant. For reactivity insertions due to water flooding or reflection, however, the increased leakage which would result may be significant and worthy of consideration in future excursion models.

This accident (water injection) is attended by a drastic change in both spectral and spatial effects in the core. The flooded end of the core is partially thermalized, while the upper unflooded core remains epithermal in its spectral character. Since the critical volume of the reflected and flooded B-4 core is larger by a factor of three than the minimum carbon-uranium-water critical system of the B-4 C/U-235 ratio, the spectral contribution is obvious, and its omission possibly a major one for water accident cases.

(3) The reactivity feedback scheme in RAC, that of proportionality of excess reactivity with core density

$$\frac{\Delta \rho}{\rho} \approx \frac{\Delta k}{k}$$

is a first order approximation. For large excess reactivities, the proportionality to core density is probably less than one (LASL estimates $\Delta k/k \sim 1/2\ (\Delta\rho/\rho)$ for insertions in excess of ~\$14).

(4) The RAC code presumes a homogenized graphite-urania mixture and does not treat the effect of (a) the neutron streaming from the .094" coolant channels, (b) the effect of the pro-carbon

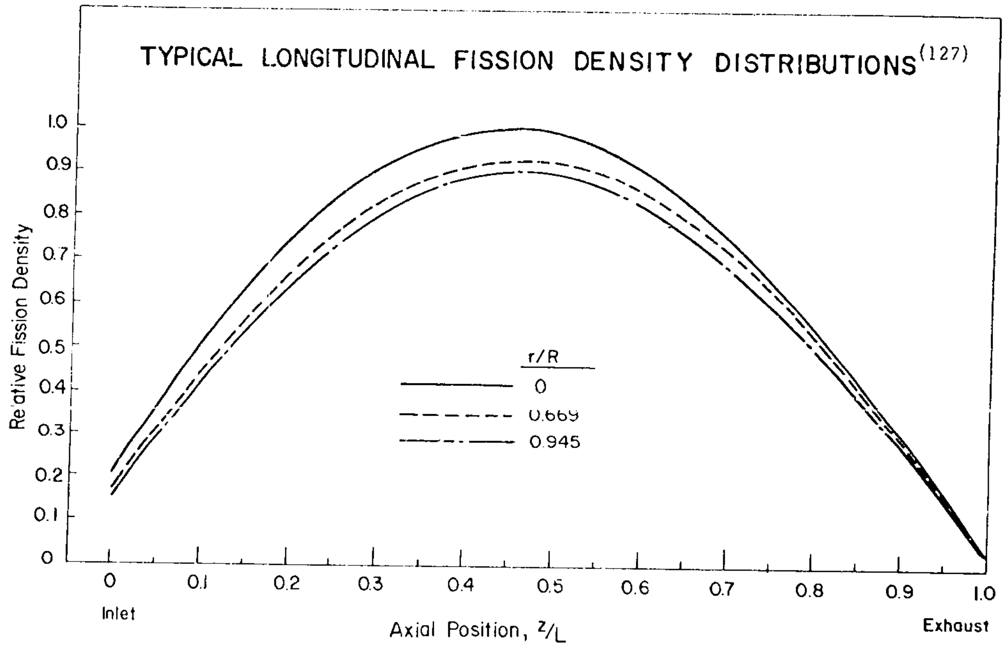

TYPICAL LONGITUDINAL FISSION DENSITY DISTRIBUTIONS(127)
Relative Fission Density
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
r/R
0
0.669
0.945
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Inlet
Exhaust
Axial Position, z/L

Figure VII-2

TYPICAL RADIAL FISSION DENSITY DISTRIBUTION[127]

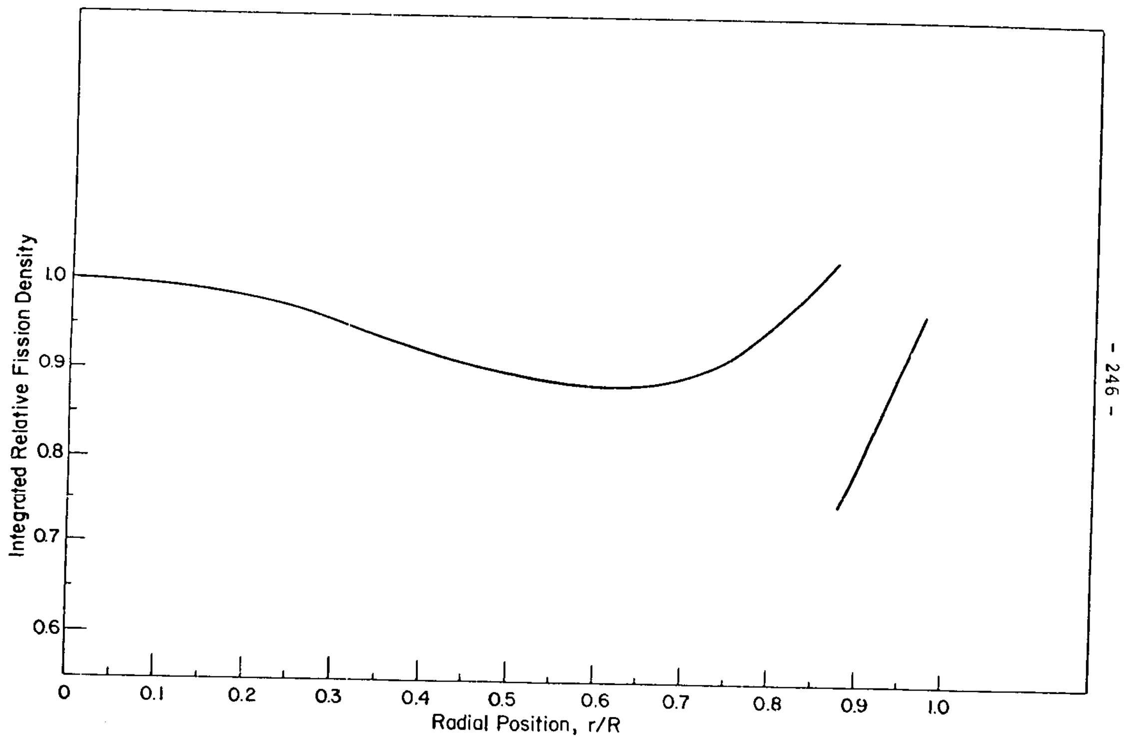


Figure VII-3

coated dispersion fuel particles on the assumed equation of state, or (c) the heat capacity of metallic core structural components, and their effect on melting and vaporization. The effect of these additional heterogenieties on actual system releases is probably not well known.

(5) As discussed in the Appendix, RAC partitions the fission energy between heat capacity, vapor formation, and melting. It is also assumed that the vapor produced during the transient remains in the immediate vicinity of the core (i.e., it occupies a volume equal to the core void space plus the volume of the loaded graphite), perhaps due to fracture of the core and plugging of the core channels for times of interest to the excursion. Recent TREAT experiments(94), however, suggest that the graphite vapor may diffuse from the immediate vicinity, either leaving the core or depositing on the cooler end surfaces. This possibility would generate yields in the shaded region of Figure A-2 due to the lessened quenching mechanism available; i.e., less than the linear extension of Figure A-2, but larger than the predicted ($0.75/1000°C) curve. On the other hand, if liquefaction is prevented but gas production (and its retention in situ) allowed, the yield curve above 1.0 dollar is lowered by 25 to 30 percent (LASL estimate). The kinetic energy for a given reactivity for this case however would be greater.

(6) RAC neglects the fact that at very high reactivities an upper limit to the amount of vapor that can be created exists (such a limit does exist for the liquid). Thus, at about $14 sufficient energy has been devoted to vapor production to vaporize the entire core. The plot of energy stored in the gas of Figure A-6 has been drawn to change curvature at $8 to $10 and approach 2.52×10^{21} fissions asymptotically; actual RAC output is indicated by the dashed line extension.

The gas and liquid production curves on Figure A-6 simply represent energy sinks (the liquid curve does not represent actual liquid content in the core -- rather the energy required to create liquid); the latent heat from solid to gas is 172 K cal/mole, while the latent heat via the solid to liquid to gas chain is 183 (11 + 172) K cal/mole. The inconsistency is small.

(7) The releases as a function of reactivity insertion rate shown in Figure A-7 unlike the other calculational data, are

computed from the RTS code by G.R.Keepin of LASL. RTS integrates the usual reactor kinetics equations over time (a space-independent assumption is made) to obtain the energy release, power responses, period, and reactivity as a function of time. The code provides good data in the reactivity regions between delayed critical and prompt critical. The RTS model is accurate at lower reactivities; in the near prompt and greater than prompt critical range, however, the neglect of delayed neutrons introduces some error in the post-peak region. (The total delayed neutron yield in very rapid transients can produce a significant power plateau in the subcritical system following the burst.) The most appropriate normalization scheme of RTS and RAC releases in this region is therefore subject to question.

(8) A major uncertainty in the RAC analysis concerns the temperature coefficient which is estimated by LASL to be ~\$0.75/1000°C for the B-4 system. Figure A-2 clearly illustrates the dependence of calculated yields on the temperature coefficient; the largest dependence (a factor of two) in fission yield occurs over the reactivity range from delayed critical to ~\$1.1 over prompt critical. Since the assumed temperature coefficient could be in error by 50%, it is only prudent to ascribe a factor of two in the computed yields of this study to this effect alone.

(9) A final and most significant uncertainty lies in the assumption of the graphite equation of state. The equation of state employed in RAC, based on the National Carbon data of Figure A-1, is discussed in LAMS-2710. LASL and WANL agree that the graphite description is sufficiently crude as to make questionable the necessity for additional elegance in the analytical representation of prompt excursions at the present time. As additional basic data are acquired on the physical behavior of graphite and its material properties in the temperature regimes of interest, or as integral experiments are performed on the KIWI reactors for RAC normalization and interpretation, the calculational refinements cited earlier should be incorporated.

Some of the present uncertainties in the materials assumptions utilized in RAC include:

(a) The latent heat of vaporization reported as 170.39 K cal/mole, whereas, RAC uses 172 K cal/mole.

(b) The latent heat of liquefaction which is considered by the National Carbon Company to be not well known (RAC uses 11 K cal/mole).

(c) Coefficients of linear expansion vary widely depending on the particular form and kind of graphite, as well as temperature. RAC assumes a constant coefficient.

(d) Coefficients of compressibility are actually undetermined for bulk graphites (though they are known for diamond and single crystal graphite).

(e) The assumption in RAC that the equation of state is descriptive of both the liquid and the solid state is speculative; there are little or no data to support the hypothesis.

In summary, the uncertainties in the temperature coefficient and material properties alone imply uncertainties in energy release greater than a factor of two, but very probably the estimates of magnitude are within a factor of three or four.

c. Release of Material-Amount and Character

As indicated in the discussion in Section IV-B, the release of material from an accident involving a given insertion of reactivity is critically dependent upon the state of the core following the transient. This definition of state includes the temperature distribution, and the physical fracturing of the core. As mentioned in Section b. above, the magnitude of excursions in KIWI - NERVA reactors is presently derived from the RAC code in which a number of uncertainties presently exist, with respect to representation of material properties and nuclear parameters.

Studies on the release of fission products from core material under transient conditions has been and is under study as reported in Section IV-B. Present plans include extension of past tests to the shortest period transients possible in the TREAT reactor and then by the NRDL in a TRIGA reactor to periods on the order of one millisecond, and perhaps 1/3 millisecond. These tests, to be conducted over the next year, should provide a good indication of the behavior of individual fuel fragments with respect to fission product release and fragmentation for given fission densities. LASL is also planning further furnace studies on newer fuel types, to develop data on release of fission products as a function of time and temperature. Integration of these microscale release data into the overall core behavior during transients with a normalized RAC computation should then permit establishment of more precise indication of fission product release as a function of reactivity insertion.

The determination of physical fractionation of the core may be somewhat more difficult to develop on the basis of presently proposed tests since the behavior of small pieces of fuel material would not be expected to be strictly analogous to an entire cluster of fuel elements with variable fission densities and temperature gradients. As indicated in the fallout evaluation of Section IV-D, determination of particle size distribution is highly significant to the doses resulting in such a case.

At the present time it would seem that the assumption of release of all of the volatile fission product elements as delineated in Section IV-B for excursion magnitudes on the order of 10^4 megawatt seconds and greater is not unduly conservative. It is estimated that the precision of the dose analysis is affected by no more than plus or minus 30 percent by this assumption. The particulate fallout dose problem, however, is one based on much more tenuous assumptions and the doses deriving from this situation may be in error by an order of magnitude either way. In particular, uncertainties arise in connection with the beta dose rate at the surface of small particles due to a lack of information on the beta energy spectrum as well as the lack of empirical correlation of beta dose measurements with the calculational model employed in this study. The gross gamma dose rates from a fallout field are much more dependent upon environmental conditions pertaining at the time of the accident and the nature of the accident itself to the extent that it determines the dispersion of particles.

Some additional uncertainty, of a relatively minor nature, is introduced by the presently available fission product inventory. Several machine codes have been written for calculation of these inventories, most of which differ slightly from each other as shown in Figure VII-4 for the radioiodines as computed by the WANL and Martin Company codes. All of these routines necessarily neglect very short-lived isotopes which contribute a significant fraction of the decay power at short times following an excursion. This contribution is most important in a consideration of the cloud doses at close-in distances.

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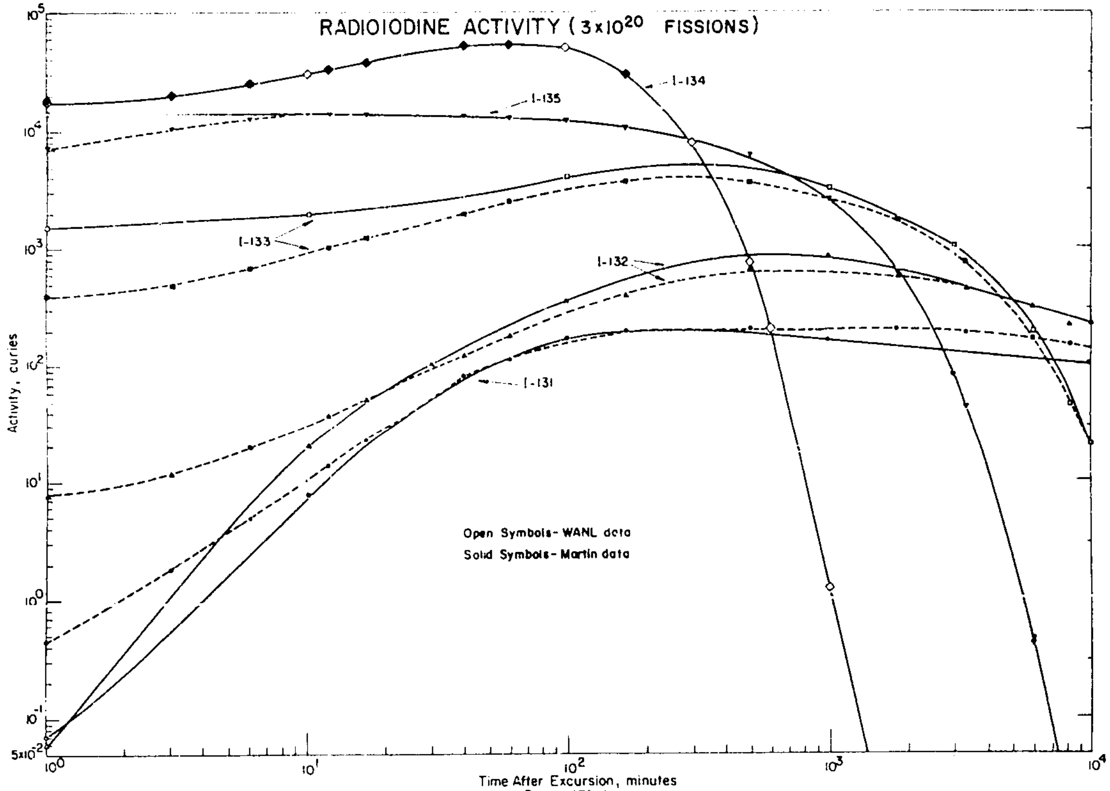

Figure VII-4

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This study has also neglected activation products in consideration of hazards. For the excursion case, in particular, the contribution of activation products to the doses caused by exposure to fission products would be negligible due to both the relatively small inventory and the generally higher acceptable body burden of these nuclides. For the reentry case, the contribution of activation products is more significant than in the excursion, but it will still probably provide a very minor contribution in comparison to the fission product inventory as shown by the Martin study[109]. When material and design parameters are more firmly established, and the activation product inventory can be calculated more precisely, this aspect should be viewed again for its significance.

d. Summary

In summary, it is felt that the combination of errors due to uncertainty in physical parameters employed in source analyses and those uncertainties arising from the inability to predict circumstances pertaining to time of an accident may result in variations of dose from those predicted in this study by factors ranging up to two orders of magnitude. This derives from uncertainties in the magnitude of excursion for a given insertion of reactivity, from the possible variations in the location of the accident, and from the release of material both in amount and physical state from the reactor core. Probably one of the larger uncertainties contributed by the source term arises in the cases dependent on the fragmentation pattern of the core which alone may affect the resulting doses by about an order of magnitude.

2. Environmental Model

In addition to the contribution of uncertainties in the source term, there are uncertainties in the treatment of the dispersion and transport of materials through the environment to man which require recognition. These uncertainties, as in the case of source definition, are related both to the inability to define precisely complex mechanisms by relatively simple mathematical models, and to the uncertainties introduced by man's inability to predict circumstances obtaining at the time of an accident.

a. Meteorology

Several analytical models employed for prediction for downwind concentrations from a source of pollution released to the atmosphere

have been presented in Section III-A. In that discussion it was indicated that the variation in downwind concentration predicted by the various relationships might span an order of magnitude from highest to lowest. The model employed in this study, that presented by Pasquill, appears to yield values which are roughly midway between the extremes of those provided by the other equations considered. It would seem, therefore, that insofar as the suitability of model is concerned, the error attributed to this source should be no greater than about a factor of three.

On the other hand, the question of the adequacy of the model to represent the conditions pertaining to the release (that is, a "puff" release as opposed to a continuous release) and the effect of the local terrain characteristics (such as land-water interfaces and the inland extent of seabreezes) is open to considerably more uncertainty.

The behavior of a "puff" release is highly dependent upon the circumstances pertaining at the time of release. A program to determine the behavior of "puff" releases would be quite difficult to establish, and unlikely to yield results which improve the reliability of estimates by a substantial factor. The effect of the terrain characteristics may be substantial, due to rise or fall of the cloud depending on conditions over water areas, and a decrease in dispersion over water areas. The flow patterns of onshore winds over populated areas are also highly important in determining the extent to which contamination released at the Cape will be transported inland.

Another highly significant parameter employed in the dose analysis is the depletion of the cloud due to deposition of material on vegetation or the ground. The significance of the deposition velocity has been pointed out in Sections III and IV and estimates of the effect of this parameter on dose have been indicated in Section IV-C. From these considerations it is apparent that the depletion rate, or deposition velocity, assumed for the various nuclides in this report will have a major effect on the inhalation dose, the dose due to deposition on ground surfaces, and the doses deriving from ingestion of contaminated food.

Deposition, although certainly not zero, is undoubtedly non-uniform along the path of a cloud, not only due to the existence of large water areas but also to differences in the type and density of vegetation. It is felt that the doses dependent upon the cloud should lie within a factor of from 2 to 10 of those estimated herein, depending upon the particular dose under consideration. For example, whole body gamma doses should not be in error by more than a factor of 2 from those computed using cloud depletion factors. On the other hand, iodine thyroid doses, and deposition and ingestion doses may be in error as much as a factor of 10 introduced by the deposition velocity pertaining at the time and location of the accident.

The models used for computation of whole body gamma dose and inhalation dose from air-borne contaminants are probably within plus or minus 20 percent for the conditions specified.

b. Hydrology

The contribution to external population exposure from the water environment has been treated only for the immersion case. Immersion doses following off-shore impact are probably conservative by no more than an order of magnitude at 10^2 to 10^3 minutes because they are based on diffusion following t^{-2} while Carpenter's dye-diffusion tests of the spring and summer of 1962 indicated a faster drop-off (averaging about t^{-3}). The contribution of additional shearing effects to the dispersion of the contaminant cloud also was not included primarily due to a lack of quantitative values for magnitude of these effects.

In the inland waterways of the Indian River Basin concentrations of contaminants at times of 10 to 10^3 minutes are probably low by one or two orders of magnitude due to the time required to achieve uniform dispersion of the released fission products in these reaches. An ameliorating influence which was not evaluated in this study is the reduction in activity in the relatively stagnant inland waterways due to sedimentation and other physical and chemical processes following a violent introduction of material into these shallow basins.

c. Food Chain Analyses

The major food items treated in this evaluation were milk and seafood. In the case of milk contamination, it has been shown in the

earlier sections of this report that the most significant isotope is Iodine-131. The assumptions involved in the estimation of the conversion of depletion per square meter to activity per unit volume of milk may vary by a factor of 2 or more in individual circumstances, depending on the grazing habits of the cattle; that is, the limiting deposition value of 0.07 microcuries per square meter might range up to 0.14 or down to .035 microcuries per square meter for Iodine-131. The distance from the source within which this value might be exceeded would then depend upon the meteorological circumstances (which are not amenable to more precise definition) and the deposition velocity.

If 0.07 microcuries per meter square is acceptable, (perhaps due to a lower grass intake per day than that assumed in this study) then control would not have to be exercised at distances greater than 70 kilometers if the deposition velocity were 0.25 cm/sec under inversion conditions, or at distances no greater than 40 kilometers if a deposition velocity of one cm/sec is valid. Under neutral conditions, however, the most restrictive deposition velocity does not appear to require that control be exercised beyond 35 kilometers, if a value of 0.07 microcuries per square meter is acceptable.

If, on the other hand, a value of 0.035 microcuries per square meter is a more realistic limit, then even under neutral conditions, control would have to be exercised out to distances of perhaps 75 km if the deposition velocity were greater than about 0.2 cm/sec.

It appears then that in the case of ingestion via milk, the deposition velocity plays a most significant role in determining the resulting doses with uncertainties introduced which appear to exceed those generated by the lack of knowledge of the dietary habits of local cattle.

No consideration has been given to the biological differences that may exist between individuals in the same age group or between individuals or different age groups (with the exception of the consideration of the child for thyroid dose from milk). It is assumed that the dose standards established by appropriate agencies recognize these variations in biological activity and incorporate factors to compensate for them in the resulting permissible dose standards.

The internal dose from ingestion of seafood is based on tenuous knowledge at this time of maximum permissible concentrations for sea water. This is due primarily to the generalized treatment of specie variability and response to the presence of most of the rarer elements in their marine environment. More information is needed on stable isotope concentrations both in the organisms and in their environment. Almost no information is available on the movement of certain nuclides through the various species of organisms present in the marine environment of Cape Canaveral. Little information is available on the uptake of rare earths and their abundance in the sea and marine sediments. All of these factors may lend conservatism to the proposed maximum permissible concentration in sea water for many nuclides in view of the large concentration factors assigned to the transition and lanthanide groups of elements.

B. RECOMMENDATIONS

1. Analytical Models

a. Source Term

(1) The model presently providing the major description of the nuclear excursion is that used in the RAC code. It seems unlikely that sufficient data can be accumulated in the near future to make any code completely descriptive of all the possible accidents. A series of suggestions are made below for the modification of the code to give more accurate results. One cannot be sure of the relative importance of the various corrections. In order to save time and effort it is suggested that each of these areas be explored using reasonable extremes of the various parameters to see how sensitive the results are to such variations. Such preliminary studies will avoid unnecessary elaboration of all of the effects. It should always be remembered that an accident is an unforeseen event and this in itself introduces a certain amount of inherent error. Parametric variations producing effects small in comparison to this inherent error are without real significance.

With respect to the RAC code routine it is suggested:

(a) effort continue to quantify and include in RAC any nonproportionality of excess reactivity with core density for large insertions, and/or establish the range of validity of the present reactivity feedback scheme (which assumes direct proportionality from axial expansion only).

(b) an extension of the one-dimensional axial model to two-dimensional r-z geometry be undertaken when additional information on the physical properties of the fuel system warrant the additionel elegance in spatial description.

(c) for the accident cases resulting in moderation or reflection by water or liquid hydrogen, the spectral effect should be incorporated through inclusion of a modified nuclear constant derived from a more appropriate scattering kernel for a core including hydrogen.

(d) recognition of the asymmetry of the hydrogenous injection and its time constants.

(e) the effect of neutron streaming from coolant channels on reactivity compensation be identified and if significant, incorporated in RAC.

(f) the possible contribution to shutdown from fuel particle vaporization during large insertions and any pressure effects therefrom be established and if significant, be incorporated in RAC.

(g) minor inconsistencies in RAC be resolved, such as the lack on upper limit to gas production, liquid reduction due to boiling, etc.

(h) that the KIWI-B4 temperature coefficient, when established by experiment, be used in future RAC analyses.

(i) that pending additional data required on the physical properties of uranium-graphite fuel systems, that RAC parametric surveys be made to assess the sensitivity of the computed energy release to program (physical) constants assumed which may be of questionable accuracy or whose temperature or density dependence is not well known; e.g., the coefficients of linear-expansion and compressibility, latent heat of liquefaction, temperature coefficient, graphite vapor diffusion from the core (rather than remaining in situ where created), etc.

(2) It is recommended that the WANL fission product inventory code be modified for both the excursion case, and the operating

case to cover a greater range of times, and smaller intervals. The range should be extended to times of at least one year, and the intervals should be spaced by no more than a factor of three. Additionally, the code should be amplified to provide data on radiation power, both beta and gamma, by energy class for each element. The energy categories for gamma radiation might follow those employed by Blomeke and Todd[97] (0-0.25 Mev; 0.26-1.0 Mev; 1.01-1.70 Mev; > 1.70 Mev). The maximum beta energy categories suggested are: (0-0.1 Mev; 0.11-0.5 Mev; 0.51-1.0 Mev; 1.01-2.0 Mev; >2.0 Mev).

(3) It is recommended that an activation product program be modified to provide the same information as the fission product routine.

(4) It is recommended that an analytical model, normalized to experiment, be developed to represent core fragmentation as a function of reactivity insertion and external forces from chemical explosions. Particle size and kinetic energy distributions are essential for a more realistic appraisal of fallout problems.

(5) It is recommended that consideration be given to the establishment of an analytical model representing the location of impact points based on appropriate past vehicle performance at or near the launch site resulting from launch aborts and of explosive yields from various failure modes of large boosters.

b. Environmental Models

Transport models are available for both atmospheric and waterborne contaminants which have performed reasonably well in many other applications. It is felt that development of new models to describe the behavior of media in the Cape Canaveral environment is not warranted. What are required are experimental programs which will permit identification of the model, or models, with which the experimental data can be effectively normalized. The dose models employed are based on generally accepted practice, and introduce relatively minor uncertainties in themselves; the important sources of uncertainty generally arise from questionable values for parameters employed in these models.

2. Additional Input Data

a. Source Term

(1) Magnitude

The pivotal emphasis in further development of prompt excursions of KIWI - NERVA reactors must be on obtaining far more information than is presently available on the macrometallurgy of carbon-urania fuel systems. It is recommended that:

(a) responsibility be specifically assigned to an individual or group to identify what data on physical properties are most urgently needed, the experimental programs necessary to obtain these data, and their priority. Progress should be reviewed periodically to assure the implementation of long-term fuel development program.

(b) that a series of integral experiments be conducted on KIWI-B4 for purposes of interpretation of power transients by the RAC (or other) code. Such experiments would serve as a vehicle for normalization of an imperfect equation of state in RAC to experiment to yield a calculational scheme which gives good checks on gross integral experiments.

(c) that full use be made of analytical and computational tools developed in support of weapons systems for purposes of computing prompt yields and by greater sophistication in reactivity feedback mechanisms be incorporated in the existing formulation.

(2) Fission Product Release

As indicated previously, experimental programs are presently in progress which will develop information on the microscale behavior of fuel material under transient conditions of increasing severity. In addition to noting the evolution of specific gaseous and volatile fission products, information on fragmentation is collected. However, integration of fragmentation data into a full-size system model should be initiated, and experimental programs developed for field confirmation of fragmentation data, both as to particle size and kinetic energy distribution.

A similar effort at improving the definition of fuel integrity under operating conditions, and subsequent reentry is also underway, and should assist in improving the description of the single particle reentry problem. Again information on specific radionuclides is preferable to gross activity consideration.

Fission product leaching from fuel fragments in sea water is still a largely unexplored area, although studies are being initiated by NRDL. Some effort should be devoted to a consideration of the effects of prior reactor operation, or transients, on the retentivity of coated-particle fuels.

(3) Location and Severity of Launch Pad Failures

Additional effort is warranted on the type and amount of energy release associated with the catastrophic failure of chemical booster vehicles. Figures used in this evaluation were based on the yields for propellant explosions currently used by the Range Safety Division, CCMTA, for vehicles much smaller than the C-5. Since this yield has a significant effect on the consideration of accident magnitude and effects, a further study of the mixing of large volumes of propellant appears desirable.

Continuing consideration should be given to probable impact areas, and limits for impact, in the launch site vicinity based on the results of refined hazard evaluations.

b. Environmental Data

Much of the data necessary for a first order hazard evaluation at the launch site are now available, or becoming available. However, much additional environmental data would be desirable before the final hazard analysis is made.

1. In the meteorological area, additional data are required with respect to the behavior of contaminants released during periods of on-shore winds as affected by the terrain; trajectories and dispersion at distances much greater than those treated by the Ocean Breeze study are essential to obtain.

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Since deposition of iodine from clouds has such a significant effect on the downwind doses, some consideration should be given to a study of this effect at Cape Canaveral. Deposition by rain also appears to provide a hazard potential, and a preliminary effort should be made to correlate the occurrence and intensity of precipitation with time of day, wind direction and speed, and stability pattern.

The planned extension of the meteorological data network to Merritt Island is necessary, but some consideration should be given to establishing stations on the mainland to correlate wind persistence and trajectories.

2. In the hydrologic area, further attention to current and dye diffusion studies is certainly warranted in the off-shore waters. In particular, the presently unresolved questions of on-shore particle transport seem most important in view of the highly significant doses that could be delivered to bathers or other beach-users. Soluble material in off-shore waters does not appear to create any major hazards.

In the Indian River Basin, diffusion studies are certainly in order -- but these studies should be conducted after the major modification planned in the Banana Creek and Banana River area are completed, if the most reliable information is to be obtained.

Some study of the ion exchange capacity of bottom sediments in both in-shore and off-shore waters would be of interest, particularly in the former case, where the only appreciable removal rate of contaminants would derive from precipitation and ion exchange (or sorption) on bottom sediments. For ocean areas relatively close to the shore the possible contaminations important to man will probably be those from ion exchange or precipitation resulting in radioactive contamination of beach sand.

Ion exchange capacities of soils at the Cape and on the mainland in the ground water recharge zones would also assist in refining estimates of water contamination following deposition. Other data required would be concerned with the travel time of percolating waters between the surface and withdrawal in wells, or appearance in the Indian River Basin.

3. Additional data on food chain transfer of radioactivity to man is of prime importance in view of the relatively significant ingestion doses calculated earlier for the air-borne release. In particular, an investigation of dairy farming is highly important, with respect to location of such farms, the feeding habits of the cattle, and the marketing routes for milk and milk products. Some review of the production of eggs, and the feeding habits of the hens is also warranted in view of the reported significance of this route for Iodine-131.

Some consideration should also be given to other crops, particularly leafy vegetables or fruit eaten raw or without skinning which may be affected by deposition from a cloud under wet or dry conditions.

A continuing review of community plans for development of surface water supplies should be made. Cocoa, for example, is reported to be considering the use of Lake Poinsett as a water source, and this will require a review of the potential ingestion dose in the event of an accident.

With respect to the marine food chain, more specific data on uptake of significant radionuclides by local species would add an increased degree of confidence to the estimate of hazard from release of fission products to water. These studies should consider both soluble activity and small particulate or collodial activity, as well as the effects of stable isotopic dilution and prior ecological reconcentration.

VIII. COUNTERMEASURE RECOMMENDATIONS

The discussion below is primarily directed toward those measures intended to reduce the effect of accidents after their occurrence. However, it is felt that many potential problems arising from accidents at the launch site could be substantially eliminated by incorporation of suitable engineered safeguards in the reactor or stage design. For example, the present efforts toward development of a core poison system should be pressed to produce, if possible, a system which will prevent criticality in the event of immersion in moderating liquids, or compression by impact on the ground or by detonating propellants. From a consideration of environmental effects, it would be desirable that the poison not be removed until the vehicle has passed out of the vicinity of the launch site (at least a 100 mile impact point downrange).

It is also understood that sensing devices which anticipate booster malfunctions have been employed on the vehicles used in the manned space flight program. If adequate core poisoning cannot be provided, some adaptation of these devices should be considered for use on the Saturn-NERVA vehicles.

There are other measures which can be taken to prevent criticality accidents on or near the launch pad. Some of these are design features apart from poisoning, discussion of which is beyond the scope of this report. Other measures relating to procedures and administrative control can, if properly carried out, prevent or reduce the probability of a nuclear excursion to the vanishing point. These are also outside the scope of this report.

Two categories of countermeasures can be used to classify the following recommendations. The first class includes those technical countermeasures based on the application of equipment, facilities, or variations in operational modes to mitigate or eliminate the effects of accidents (or normal operations). The second class includes those administrative measures designed to reduce hazards by controlling the location, behavior or habits of workers and off-site residents.

A certain amount of control of accident consequences can be exercised by modifying operational modes. If the guidance systems are sufficiently reliable, initial flight paths can be selected which place the locus of possible nuclear excursions as far away as possible in distance and downwind angle from workers or off-site population. The location, angle of flight, and lift-off program of the vehicle for mandatory destruct could also be selected more restrictively than is used for purely chemical fueled vehicles, but this imposes the penalty of greater probability of an unsuccessful launch.

Restriction of launching times to those when meteorology is most favorable for protection of site and environment, both as to wind direction and dispersion conditions could be invoked , but would reduce available time for launch. It is to be hoped that means can be found in design and operation so that this kind of interference with the program can be avoided. Studies thus far give some assurance that this can be achieved.

Three basic tenets of radiation protection have been frequently listed as "time, distance, and shielding". These basic considerations can be used to indicate possible countermeasures, with some semantic distortions. The "time" or duration of exposure can be controlled for some sources of exposure; the "distance" can be replaced by a separation of the receptor from dose sources; and "shielding" can be considered literally, or as physical sequestration of the source (in some cases). Each of these approaches will be considered for the three classes of accidents analyzed in this study.

A. NUCLEAR CRITICALITY ACCIDENT

1. Technical Countermeasures

An initial consideration pertinent to all accidents which release material to the atmosphere is the requirement for monitoring, the delineation of the path of the cloud, and the extent of residual contamination. It is anticipated (and recommended) that the present (or modified) WIND system will be extended to include the new Merritt Island area, and will provide an extension of a diffusion prediction feature to the much larger area potentially affected by an accident.

It is suggested that consideration be given to the installation of gamma monitoring devices on selected existing (and proposed) meteorological towers prior to nuclear operations. These devices would confirm the cloud trajectory indicated by WIND, provide a rapid, though crude, indication of the magnitude of the release, and sound alarms in the appropriate on-site locations. It is assumed that area monitors will be provided in those facilities in which the reactor and nuclear stage will be assembled, tested, and mated to the rest of the vehicle.

Except in highly unusual circumstances, no time will be available for evacuation of workers or residents prior to cloud passage; therefore, the external cloud and inhalation doses cannot be effectively reduced by limiting the duration of exposure from these sources. Protracted doses resulting from deposition of radioactive material can be controlled, however. For this purpose, provisions should be made for monitoring residual contamination, both on- and off-site.

Mobile monitoring devices should be provided which are capable of measuring surface contamination dose rates over relatively large areas quickly. This can be done by light aircraft for off-site areas and by cars, trucks or helicopters equipped with sensitive gamma detectors on-site. Additionally, monitoring and analysis equipment should be available for prompt analysis of samples of water, milk and other foods.

Reduction of residual contamination in off-site areas will be limited to relatively few areas and items. Automobiles and paved streets can be adequately decontaminated by hosing with water, and contaminated fruits can also be washed prior to use. The levels of exposure from such sources, however, would probably be very low in any event, and advance provisions do not appear warranted. On-site contamination levels, however, would be much higher, and provisions should be made for ease of facility decontamination.

Structures should be provided, where possible, with non-porous surfaces, and high pressure water available for hosing. Paved areas should be provided with drains which discharge to the ocean or perhaps suitable holding ponds rather than to the Indian River, if future studies show poor retention capacity or a short transit time from the ground surface to the inland waters or swamps. Equipment should be available to pave over badly contaminated areas, or to cover contaminated areas with sand for shielding and source isolation. Personnel protection (gas masks, self-contained breathing devices, coveralls, etc.) and monitoring devices should be available for workers employed in such activities. Consideration should also be given to the provision of remotely-operated, or shielded mobile devices capable of recovering a highly radioactive reactor or engine (or fragments) following a criticality accident at the launch site.

Some consideration should be given to the situation in which the reactor is made critical to a degree which is insufficient to destroy itself and which results in a continuing generation of fission products.

Partial immersion in water and chugging might be such a case. The possibility of an occurrence of this type seems quite remote but means for disassembly or poisoning might be relatively easily provided. Some further consideration should be given to such countermeasures.

2. Administrative Countermeasures

The basic administrative countermeasure is the preparation of an adequate radiological safety emergency plan covering all foreseeable emergencies. This plan should include specification of lines of authority, on-site and off-site individuals to be notified, assignments of responsibility, warning or alarm system signals, and a detailed description of actions to be taken as a function of easily measurable or observable phenomena, as well as the location of emergency equipment to be used. The preparation of such a plan would be extremely premature at this time; however, certain basic precepts can be indicated.

Whenever the reactor, engine or nuclear stage are manipulated or handled in a manner which may result in an excursion, all individuals not directly associated with the particular operation should be excluded from the vicinity. Evacuation, or radiation emergency alarm systems should be provided (and exercised occasionally), and workers in specific areas should be instructed in procedures to be followed in the event of alarm.

An information and command center should be designated and emergency teams should be trained and available in event of accident, with specific stations and assignments. These would include monitoring and traffic control teams for both on-site and off-site areas, and might well include representatives of local civil defense, police and fire-fighting organizations, if qualified.

An inventory of sensitive off-site areas should be maintained on a current basis, including in particular, the dairy and poultry farms. Arrangements should be made for prompt sampling of milk and eggs, as well as municipal surface water supplies, and other less immediate sources of ingestion doses, such as fruits and sea food.

The information center should have available for immediate reference the meteorological conditions existing at the time (wind velocity and direction, dispersion conditions, rain, etc.), with estimates of the delivered doses at various locations and distances as well as forecasts for the immediate future. It should be prepared to provide

accurate and timely instructions to site workers and off-site residents, and serve as a common source of information for all.

Arrangements should be made to instruct site medical personnel and workers in the treatment of radiation injuries, and such training should be extended to selected local physicians.

B. BOOSTER FAILURE ACCIDENT

1. Technical Countermeasures

Many of the suggestions made in the preceding section would be equally applicable to this class of accidents in general, although specific recommendations vary. For example, the monitoring of the cloud could probably not be effectively accomplished by the meteorological tower instrumentation due to the height of the release, and perhaps a lack of advance knowledge of upper wind patterns. In this case also, the potential areal extent of contamination is considerably greater than that in the case above, and cloud tracking by aircraft would provide the most reliable data on trajectory, since ground level concentrations of volatile material would be extremely low.

Specific problems peculiar to this class of accident are those deriving from particulate deposition and the resulting contamination of ground areas and individuals. This class of accidents does not, however, appear to require any significant additions to the technical countermeasures suggested for the preceding case. Monitoring,recovery and decontamination equipment and facilities would be suitable for either type, with perhaps the additional specification of emergency showers for personnel decontamination.

2. Administrative Countermeasures

Again, the countermeasures employed in the event of this type of accident would be very similar to those specified earlier. However, in this case, special attention must be devoted to the control of traffic, both on- and off-site, and to the prompt decontamination of individuals exposed to the fallout. The on-site problems might be minimized by requiring that protection from particulate fallout be employed by all individuals not required by function to be out-of-doors during the launch. Instructions on self-decontamination in the event of this accident should be made available to all workers and residents in the downwind area at the earliest possible time following the failure. Arrangements could be made with local agencies for public address and radio announcements, once the pattern of deposition has been established by monitoring.

C. MARINE RELEASE ACCIDENT

1. Technical Countermeasures

The release of radioactive materials to waters in the vicinity of the launch site require slightly different countermeasures and a lesser degree of urgency than the first two accidents considered. Monitoring requirements for this class of accidents would be restricted to a much narrower type of program. Recovery or isolation of the source would be highly dependent on the magnitude of the excursion (with the resulting degree of fragmentation and dispersion) and the location (whether shallow in-shore waters or shallow or deep off-shore waters) of the impact.

In shallow waters, recovery of an intact, or nearly intact, core would be feasible. However, the likelihood of an intact reactor existing following water immersion is poor. The feasibility of recovering small fragments underwater remains to be demonstrated. Similarly, the encasement, or sealing of an intact core with underwater concrete placement would be relatively simple. However, attempts to sequester a large number of widely distributed particles by concrete emplacement might require large amounts of concrete. If the leaching rate of fission products from core material is high, substantial releases to the water may take place before isolation is accomplished. For some of the local water volumes, isolation may be accomplished by damming affected reaches with less expenditure of time and money.

In the event of confined water volume contamination, some consideration should also be given to the poisoning of all contained aquatic biota to prevent their use as food by humans, since the purification of such waters by natural means would be slow.

For off-shore water immersion, considerable sophistication in instrumentation will be required to find fragments of the reactor core, and sealing of these fragments will be more difficult than in the case of inland waters, particularly at greater depths. Recovery of fragments of appreciable size can probably be accomplished with remotely operated underwater handling devices already in use, but the effort would be expensive and time-consuming.

Provision should be made for monitoring of shallow water and beach areas if impact occurs in or near the surf zone for particles washed up on the beach, depending upon the results of the study of particle wash up considered earlier in the report.

2. Administrative Countermeasures

In this case, the major effort will be required for monitoring and controlling the use of affected water volumes for the period of time required to alleviate the hazard. Particularly for the Indian River Basin, a wide dissemination of information on the restrictions on water use for bathing or fishing will be required, including the posting of signs, etc.

Monitoring would also be indicated at those harbor areas where boats are docked and serviced to detect accumulations of activity by aquatic growths on boat hulls and fittings; and at ports of entry for commercial and charter fishing boats.

IX. SUMMARY AND CONCLUSIONS

This study presents a preliminary evaluation of hazards resulting from nuclear rocket operations at Cape Canaveral. The analysis has been conducted recognizing that, at present, system parameters are imperfectly known. Continuing estimates of potential hazard are important to help indicate those areas in which more study and development are required and to assist in defining system requirements.

The frame of reference with respect to operations employed in this study assumes that the reactor would not be intentionally started until the point of impact of the vehicle had passed beyond the Blake Escarpment, some 200 miles offshore. With this assumption, the only radiological hazards at the launch site result from accidents prior to and upon launch, and the greater part of this report deals with the possible consequences of such accidents.

Radiological hazards may also derive from the reentry of the nuclear stage following operation in the suborbital flights programmed for RIFT, and these are examined in the light of much sparser downrange environmental data.

The environment of the launch site at Cape Canaveral has been examined for factors affecting the transport of released toxic materials to humans. A primary role is played by the meteorology of the area in this transport. Sufficient data were readily available to permit the establishment on a preliminary basis of the limiting and average diffusion conditions. It has also been possible to define the major routes of radioactivity intake via the food chains that exist in the area. Milk, although sparsely produced, does provide a significant route to humans for radioiodines and should be monitored carefully in the event of accidents releasing material to the atmosphere. Water supplies are predominantly underground, and hence protected at present, but future growth of the mainland area near Cape Canaveral may require development of surface water supplies which are more vulnerable to contamination. Seafood is a potential source of ingested radioactive material in the event of accidents releasing fission products to the marine environment, although in this case time is available to apply control measures as would be the case in contamination of most agricultural products.

As mentioned above, in the normal course of events a nuclear upper stage should create no radiation hazard at the launch site. However, in the course of assembly, testing and launching a vehicle, accidents are possible which may result in the formation and possible release of fission products from the reactor. The judgment has been made in this study that nuclear and environmental parameters are not sufficiently well known at present to warrant highly detailed analysis of specifically defined accidents. Instead, this report outlines three classes of accidents at the launch site which are intended to bound a much larger number of possible but indefinite accidents.

The first class represents those nuclear criticality accidents which may release fission products to the atmosphere with essentially no addition of chemical energy, yielding a ground level puff release. The fission energy release for this class of occurrences is assumed to approximate 10^4 MW-sec. The fission product release is estimated largely from a consideration of the characteristics of the KIWI B-4 core, and the results of a computer program developed at LASL (RAC) which attempts to define the state of the core following insertions of reactivity. Other factors which affect the release are derived from studies of fission product releases from graphite fuel elements under high temperature conditions. Additional work is needed (and is underway) to refine knowledge in both of these areas.

For this first case, transport of gaseous and volatile fission products via the atmosphere is considered, assuming it is valid to apply continuous-release diffusion parameters to the puff release case, and the resulting direct whole body exposure, inhalation and ingestion doses to on- and off-site individuals are computed for several meteorological conditions. On the basis of the assumptions made, it appears that overexposures to radiation would not occur to on-site or off-site populations from accidents occurring at or near Pad A. Radioactive iodine is the source of the most restrictive exposure, both in terms of inhalation by on-site workers and via milk to off-site residents. Under unfavorable meteorological circumstances, it appears that control of milk supplies for some 50 or more miles from the accident site might be required.

The second class of launch site accidents represents those accidents involving a release of both nuclear and chemical energy. The NERVA engine will be boosted by a Saturn C-5 vehicle which contains a large inventory of RP-1, LH_2 and LOX. The Range Safety Division at Patrick AFB has employed a scaling relationship to estimate the maximum yield from a booster explosion, which when applied to the Saturn-RIFT vehicle, indicates a maximum yield equivalent to about 10^6 pounds of high explosive. This yield may cause an excursion, either from core compression or from moderation and reflection by liquid propellants, in the order of 10^5 MW-sec. The total energy release creates a cloud rise which effectively serves to reduce ground-level doses from gaseous and volatile fission products. The same energies, however, may create and disperse small particles of the reactor which can deliver highly significant beta radiation doses to exposed skin surfaces. The fragmentation of the reactor core, the fractionation of fission products between these fragments and the atmosphere, and the initial rise of these fragments all play a highly significant role in determining the degree of severity associated with this mode of dose delivery, and are worthy of additional study.

The third accident class considered represents those occurrences resulting in the injection of fission products into the aqueous environment of Cape Canaveral. Recent LASL estimates of fission energy release upon nozzle-down, high-velocity entry of the intact reactor into water range in the order of 10^5 MW-sec. However, it seems reasonable to assume that in the event of such an occurrence a major fraction of the core would be vaporized, and the materials would be largely released to the atmosphere rather than to the water. For the purposes of evaluating the effects on the marine environment, a lesser release of 10^4 MW-sec is chosen, fission products from which are assumed to be completely retained in the aqueous phase. Dispersion analyses, and comparison of resulting concentrations with values recommended by the NAS-NRC, indicate that releases in offshore waters would require control of fishing activities for only short periods of time (less than one week). Deposition of significant fission product inventories in inland waters would produce a substantial problem since the depletion of activity in such confined water volumes would occur primarily by decay; the efficacy of natural sedimentation, sorption and precipitation mechanisms in removing soluble activity are not known, nor are data yet available on the retention characteristics of fuel fragments immersed in a brackish or highly salty water.

The ultimate disposal of the reactor following suborbital flight has been given some consideration. Reentry of the intact reactor has been considered following operation producing about 2×10^6 MW-sec of fission energy. If an excursion upon water entry is assumed which destroys the core, and prior depletion of volatile fission products had not occurred from decay after-heat or reentry heating, it is shown that

doses deriving from airborne contaminants would be significant for considerable distances from the point of entry. Concentrations in the ocean would not appear to create any significant problem. However, in fact, the materials causing the major portion of the atmospheric-transported dose should be released from the core prior to its impact in the ocean. If the reactor is destructed before reentry into the atmosphere, then the questions raised with respect to particle size distribution in the booster explosion case are pertinent in this case, since small particles of a destructed core, upon random reentry, may deliver unacceptably high doses to exposed skin surfaces.

Some discussion of radiation protection standards and their applicability to the ROVER program is presented. It appears that, in common with other activities of the atomic energy industry, some policy guidance is needed with respect to the doses permissible under accident conditions both to workers and to residents in the vicinity of the site. It should be noted, however, that the present analysis does not indicate that doses in excess of the currently accepted values for either group are likely to occur under the assumptions made with respect to probable location and severity of site accidents.

It should be emphasized that the conclusions reached in this study are based on the best data and judgments available at the present time. Continuing work is required to correct the dose estimates as new data become available. It is likely that doses may be reduced by proper countermeasures and emergency procedures, some of which are yet to be developed. The major conclusions reached in this study are, in brief:

1. Although several significant source and environmental parameters are imprecisely known at present, it is felt that the hazards from launch site accidents, as defined by dose levels, are probably not in error by more than an order of magnitude (up or down). These doses do not recognize, in their derivation, the possible application of countermeasures or emergency procedures which could be applied to reduce them.

2. The study has shown the difficulty of defining the acceptability of various degrees and kinds of doses to both on-site and off-site personnel. Guidance by appropriate agencies is needed in this regard to indicate what radiation standards should be applied to the several groups of individuals involved.

3. The doses from launch site accidents appear to offer significant but not insurmountable hazards from nuclear rocket flight operations at Cape Canaveral. However, it is strongly recommended that present efforts to provide an adequately poisoned core prior to and immediately after launch be intensified; this design criterion would eliminate substantially all potential for launch site radiological hazard. If this is not feasible, it is recommended that new and improved range safety techniques be employed in conjunction with a destruct or other anti-criticality device.

4. The concept for ultimate disposal of nuclear stages following operation has been primarily concerned so far with the destructive disassembly of the core into small fragments prior to atmospheric reentry. Unless burnup of these core fragments to final sizes on the order of a few to 10 microns can be assured, a preliminary evaluation indicates that severe skin damage may be produced by high beta radiation doses from larger particles. Alternative approaches to the suborbital reentry case may be indicated, which range from permitting the directed reentry of the intact reactor into isolated deep ocean areas to fragmenting the core into subcritical portions at low altitudes above the ocean surface. Consideration should be given to the advantages and disadvantages of orbital startup as an alternative. For the orbital case, the most obvious approach is to restrict reactor operation to orbits of long lifetime, or to "store" the spent reactor in an orbit of long lifetime so that substantial decay takes place prior to reentry. Appropriate guidance and propulsion system interlocks would be desirable in these cases.

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APPENDIX A

I. INTRODUCTION*

Some of the characteristics of epithermal reactor accidents which are sufficiently severe to cause a prompt neutron excursion have been discussed in Section IV-B with particular reference to the NERVA B-4 system. The calculational routine used by LASL to compute the cited fission yields as a function of extreme reactivity insertions is described in this appendix, due to the importance of the routine to the six B-4 accident cases reviewed. The releases computed for these cases were categorized and coalesced to support the selection in this study of three classes of releases not associated with specific causal events for subsequent environmental transport and dose calculations.

In the NUS judgment, uncertainties in the excursion analysis, fission product release rates, and environmental transport model do not warrant further quantification of doses from the many conceivable releases attending causal events which can be postulated. On the other hand, through the effort of LASL, special emphasis has been placed on generating as realistic a series of releases for the cases which are considered as is presently possible to do, and, therefore, an appreciation of the routine used for this analysis is important.

II. RAC CODE

The ROVER reactor power transient calculations which form the basis for the accident cases analyzed herein are performed with the RAC digital computer code by Dr. C. G. Chezem. The RAC code is a first attempt to describe the dynamic behavior of a ROVER reactor during a prompt transient. Certain features of the code are quite new; the code is therefore in an evaluationary period with additional refinements and changes in program constants being incorporated through time. The RAC code had its origin in the interpretation of the integral Godiva prompt burst experiments at Los Alamos, where quite satisfactory agreement with experiment was obtained after normalization of the calculation to the Godiva assembly (through adjustment of nuclear constants to yield appropriate prompt alphas

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*During the last stages in preparation of this report, LASL has released a detailed evaluation of KIWI transients in RFS-135 which has been received too late to incorporate in this study. The description of RAC and the results contained herein are based on personal communication with Drs. W. R. Stratton and L.D.P. King at LASL.

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for the prompt and the delayed critical masses, and the identification of an appropriate equation of state for uranium metal).[124] The extension of this earlier effort by Los Alamos for NERVA analyses has had as its aim the incorporation of an equation of state for graphite rather than uranium metal -- and a pseudo cylindrical geometry rather than spherical. For calculation purposes, the NERVA B-4 assembly is divided into a number of squat, adjacent cylinders or mass points. Each mass point or region is characterized by nuclear, thermodynamic, and material constants, e.g. transport and fission cross sections, neutrons per fission, heat capacity, mass, volume, etc. The neutron flux density assigned each mass point is then a function of axial height (the radial distribution is assumed flat), since the various quantities which characterize a mass point are considered constant throughout the region represented by the mass point.

The calculation is necessarily cyclical. To describe the step advancement of the problem, assume these variables are known: interface axial heights, H_i (t); axial velocities, $\dot{H}_i$ $(t - \Delta t/2)$; accelerations, $\ddot{H}_i$ (t); neutron flux, $\Phi_{i-1/2}(t - \Delta t/2)$*; and material temperatures, $\Theta_{i-1/2}(t)$. The problem is advanced first by advancing interface velocities:

$$\dot{H}_i(t+\Delta t/2) = \dot{H}_i(t-\Delta t/2) + \ddot{H}_i(t)\,\Delta t$$

Axial interfaces are then advanced by:

$$H_i(t+\Delta t) = H_i(t) + \dot{H}_i(t+\Delta t/2)\,\Delta t$$

The total neutron flux is then advanced in time by:

$$\Phi_{i-1/2}(t+\Delta t/2) = \Phi_{i-1/2}(t-\Delta t/2)\exp \alpha(t)\,\Delta t$$

(Alpha at cycle t is a function only of geometry and material, and is obtained from a new neutron spatial calculation every five or ten cycles.) The fission rate per unit mass is derived from the new spatial distribution:

$$E_{i-1/2}(t+\Delta t/2) = k\Sigma^{f}_{i-1/2}(t+\Delta t/2)\Phi_{i-1/2}(t+\Delta t/2) x V_{i-1/2}(t+\Delta t/2)$$

*Time derivatives of the variable are denoted by dots.

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where: k = energy release per fission (= 190 Mev/fission assumed which accounts for the fact that fission fragment delayed gamma activity does not reach saturation)

Σ_f = material macroscopic fission cross section (cm^{-1})

V = specific volume (cm^3/gm)

From the fission energy rate per mass point, the total energy release is obtained simply by summing in time and space.

Next the thermodynamic work done by this mass point on its neighbors is computed. For this purpose a temperature dependent equation of state is required. If the fission energy generated in mass point i-1/2 in the cycle interval Δt is deposited as internal energy (excepting its thermodynamic work on its neighbors), the temperatures are advanced by:

$$\theta_{i-1/2}(t+\Delta t) = \theta_{i-1/2}(t) + \dot{\theta}_{i-1/2}(t+\Delta t/2)\Delta t$$

where:

$$\dot{\theta}_{i-1/2}(t+\Delta t/2) = \frac{1}{C_{i-1/2}(t+\Delta t/2)}\left[\dot{E}_{i-1/2}(t+\Delta t/2) + \theta_{i-1/2}(t)\left[\frac{\partial P}{\partial \theta}\right]_{i-1/2}(t)\,V_{i-1/2}(t+\Delta t/2)\right]$$

With new temperatures derived, the equation of state is invoked to obtain new pressures:

$$P_{i-1/2}(t+\Delta t) = P\left[\theta_{i-1/2}(t+\Delta t), V_{i-1/2}(t+\Delta t)\right]$$

New accelerations are then found easily by:

$$\ddot{H}_i(t+\Delta t) = \frac{H_i(t+\Delta t)}{M_i} \times \left[P_{i-1/2}(t+\Delta t) - P_{i+1/2}(t+\Delta t)\right]$$

In this last equation, M_i is a suitably defined mass associated with the disk height, H_i. The problem has advanced one cycle and the interface velocities are again readvanced for the start of a new cycle.*

In summary, the code cyclically generates fission energy at each mass point, increasing temperatures and internal pressures as required by the graphite equation of state assumed. During each cycle, the mass points also perform thermodynamic work on adjacent mass points through their common interface to relieve internal pressures accompanying thermal expansion. Reactivity compensation occurs through axial core expansion.

Table A-1 summarizes the program constants relating to the graphite system which are approximated in RAC.

TABLE A-1

a.	Latent heat of vaporization:	172 K cal/mole
b.	Latent heat of liquefaction:	11 K cal/mole
c.	Coefficient of linear expansion:	4.9 to 7.8 x 10^{-6}/°C
d.	Specific heat of uranium-graphite system:	3.35 joules/cm^3 C

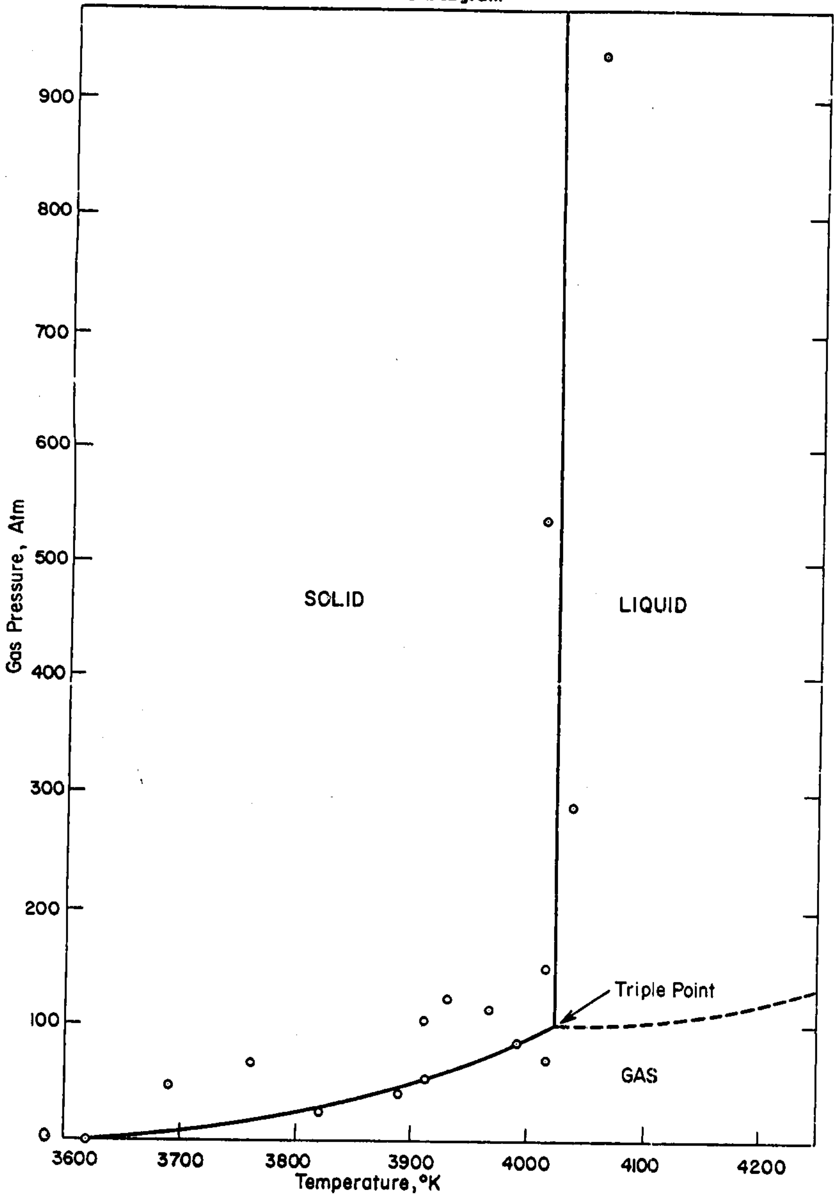
The graphite equation of state, together with the material properties of the graphite-uranium fuel system (e.g. latent heats of vaporization and liquefaction, coefficients of compressibility and expansion, triple point temperatures and pressures, etc.) are of direct importance to the accuracy of computed releases.

The equation of state (see Figure A-1) to which the above exponentials are fitted are based on a more recent determination of the triple point by the National Carbon Company than that previously reported.(125) (A triple point value of 3960°K, 100 atmospheres is now inferred by National Carbon. This value has recently been approached by a triple point inference by the General Electric Company of 4073°K, 100 atmospheres.) (126) The scatter in the data of Figure A-1 underscores the difficulty of physical measurement in this temperature regime.

Of equal or greater importance to the accuracy of computed releases is the value of the reactivity coefficients of the B-4 system. The B-4 temperature

* This same formulation in spherical geometry is treated in detail in Reference 124.

Figure A-1
Carbon Phase Diagram[125]



coefficient is yet to be established experimentally; an estimate by LASL is $0.75/1000° C. This value ($0.75/1000° C) has been assumed for this survey: the fission energy release scales inversely with this constant -- a larger value produces a smaller yield. For purposes of comparison, other cases have been conducted for temperature coefficients about this value ($0.60 and $1.20 per 1000° C), and these are depicted in Figure A-2 to bound the effect, although as noted, the value is not yet established experimentally.

To obtain insight in the predicted dynamic behavior of NERVA B-4 - Figures A-2, A-3, A-4, A-5, and A-6 are calculational results from RAC for step insertions of reactivity which attend abrupt changes in reflection or moderation (e.g., a water impact), core geometry (deformation from land impact), etc. The fission energy release for a wide range of initial reactivities is depicted in Figure A-2. It is seen for initial reactivities less than ~$1.1 over prompt critical, the fission yield is essentially proportional to the excess reactivity; that is, the core expansion is in near equilibrium with the fission energy release. For values above $1.1 prompt critical, reactor temperatures are found in the vicinity of the triple point and some portion of the core will melt and vaporize as shown in Figure IV-8. The high internal pressures developed produce an effective quenching mechanism, thus producing an energy release less than is obtained by the extension of the energy release line for insertions of less than $1.1 over prompt critical. On the other hand, at still higher values of insertions, energy is generated faster than the system can return to equilibrium; thus, the total fission yield is observed to increase. It is noted that any uncertainties in the material properties of graphite have their principal effect in establishing how far beneath the linear extension of the yield curve above $1.1 over prompt (i.e., the shaded area of Figure A-2) the actual B-4 system may be expected to behave. It is a corollary, however, that if in fact a larger fraction of the core should be vaporized for a given insertion than predicted by RAC, larger graphite vapor pressures (than identified in Figure A-3) would occur, increasing the energy stored in the graphite vapor (above that shown in Figure A-4), even though a lesser fission yield and hence a lower total system kinetic energy (than identified in Figure A-5) would result through an accelerated quenching mechanism. The total system kinetic energy from the production of high pressure graphite vapor is quite significant as seen from Figures A-4 and A-5 as functions of initial

Figure A-2
NERVA B-4 Energy Release Versus Reactivity Insertion (128)

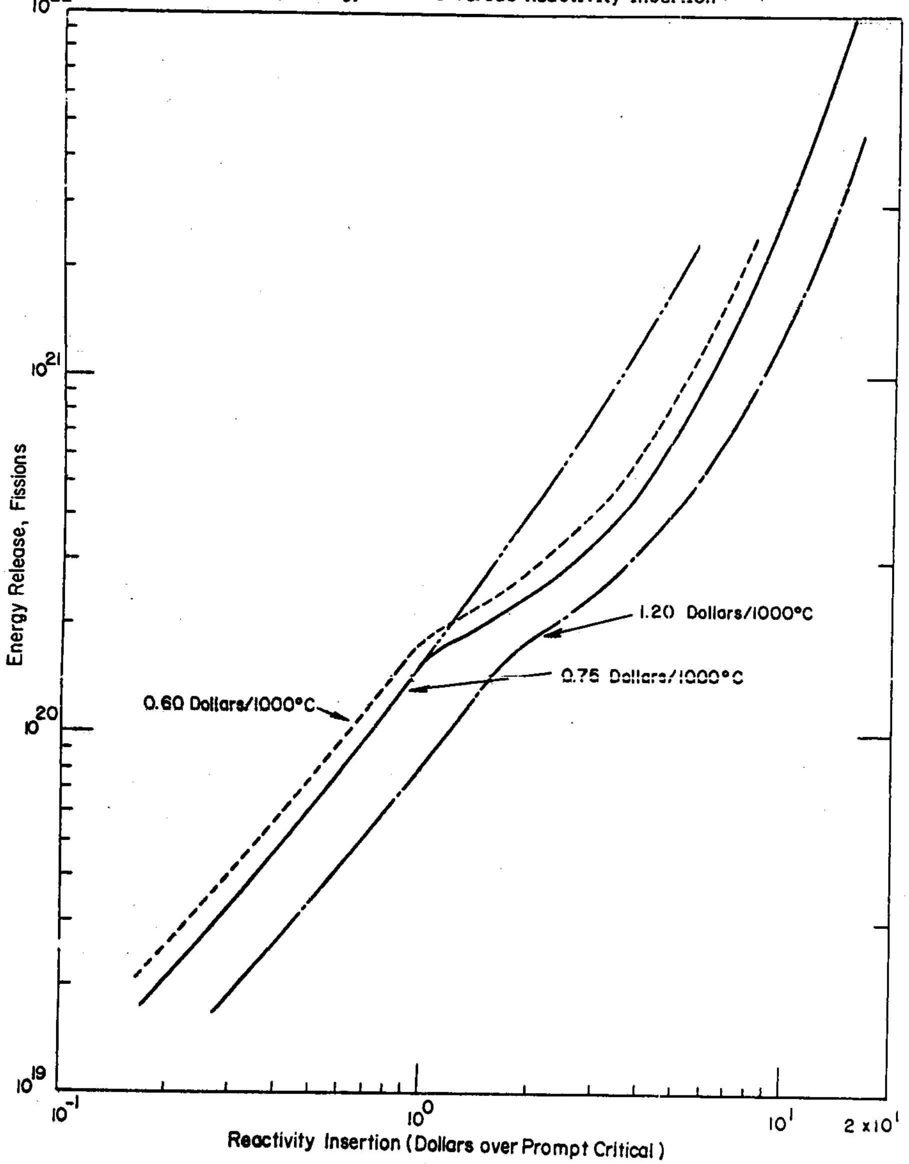


Figure A-3
NERVA B-4 Graphite Vapor Pressure
Versus Reactivity Insertion (128)

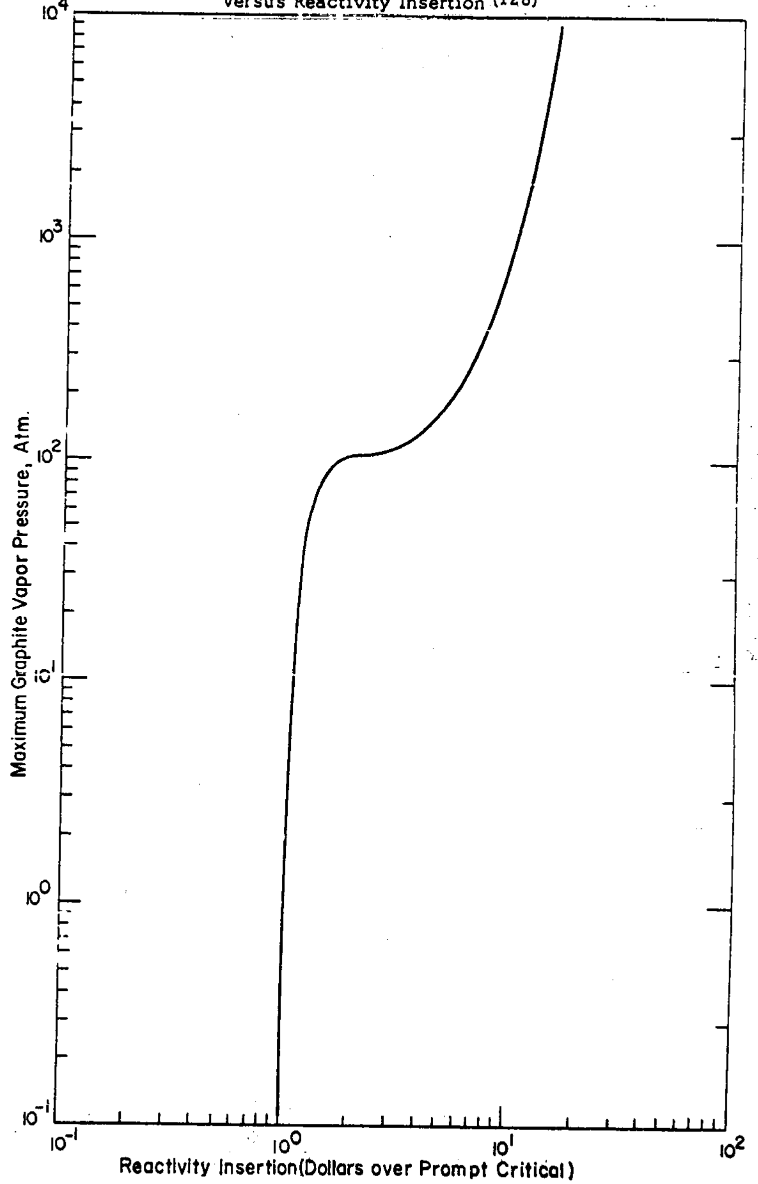


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Figure A-4

NERVA B-4 Graphite Vapor Kinetic Energy Versus Reactivity Insertion (128)

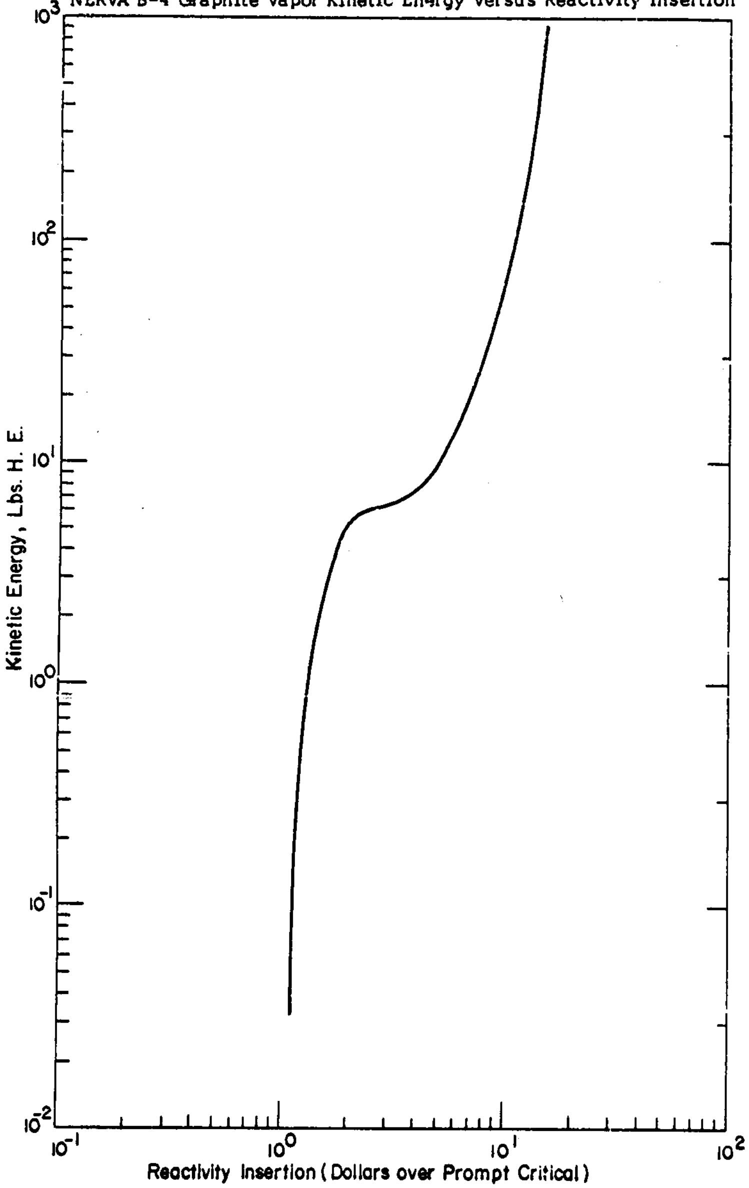

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Figure A-5

NERVA B-4 Graphite Vapor Kinetic Energy Versus Total Energy Release (128)

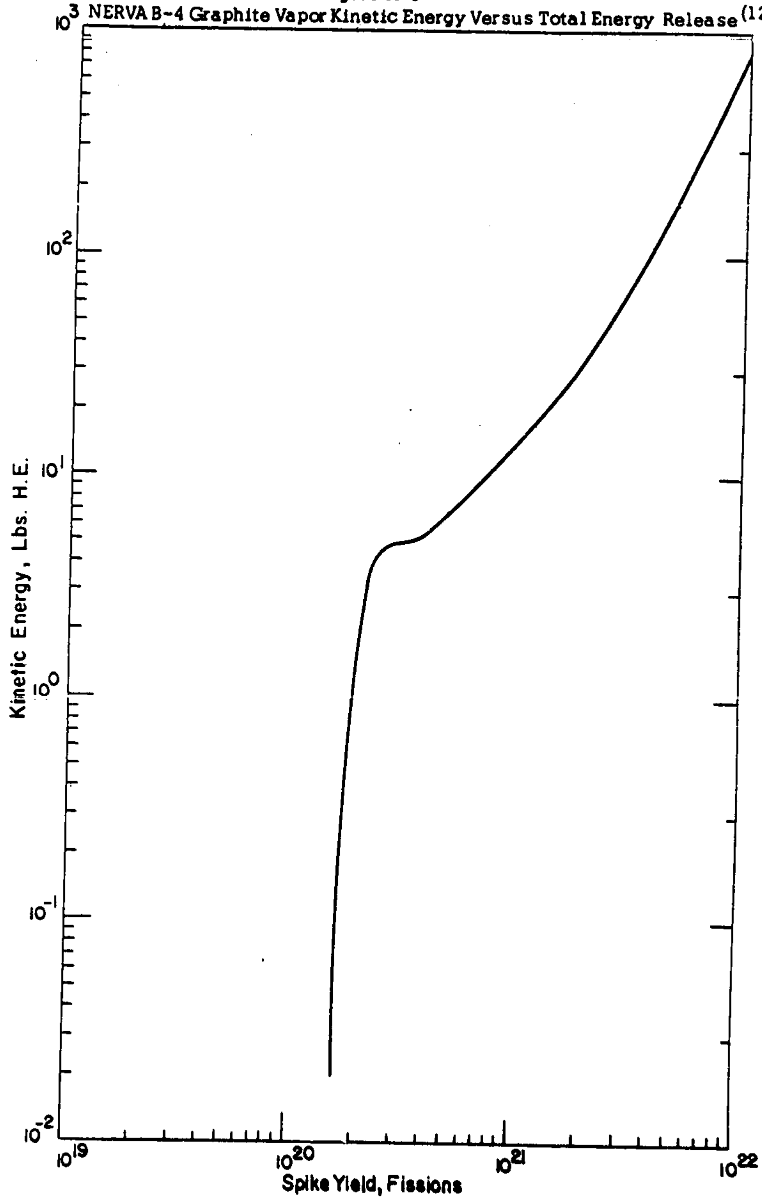

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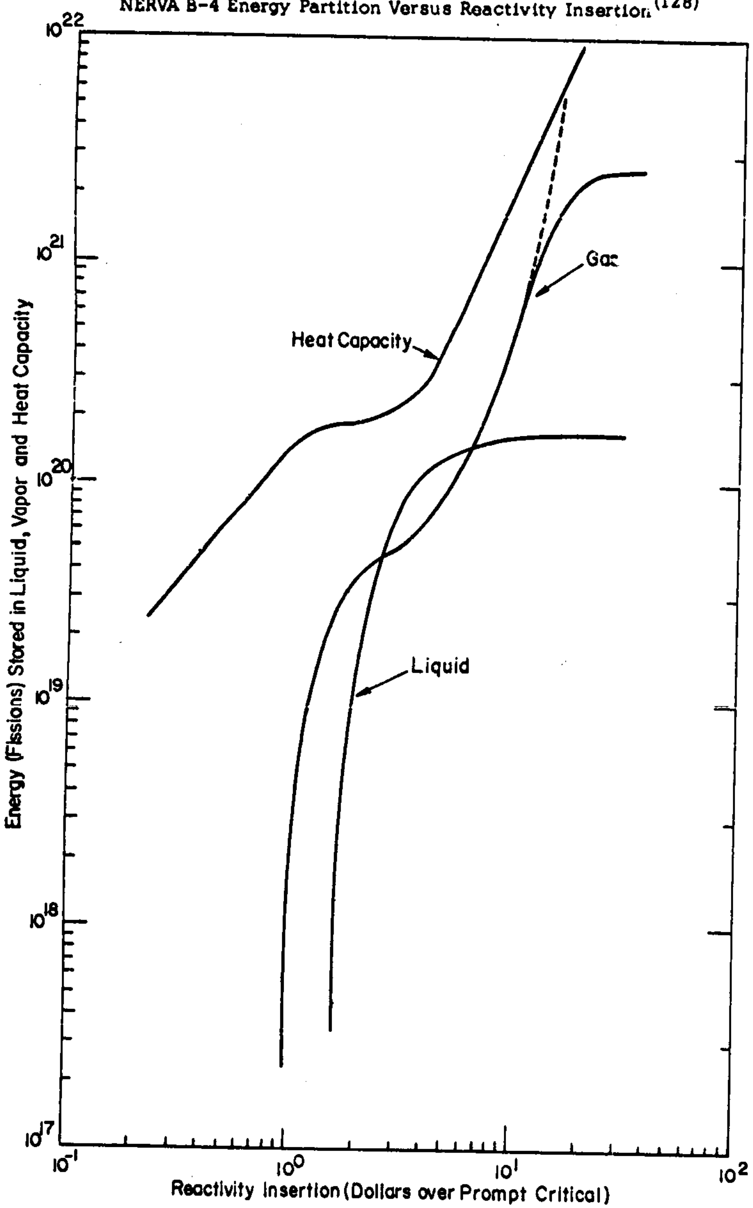
Figure A-6
NERVA B-4 Energy Partition Versus Reactivity Insertion[128]



insertion and total fission energy, respectively. The sharp break or threshold at about \$1.1 is due to initial core liquefaction. Figure A-7 depicts the maximum power levels attained in the fission spike for various reactivity insertions.

Figure A-8 presents the total fission energy release as a function of a ramp insertion rather than the step insertion characterized in Figures A-2 through A-6. The ramp commences with no time delay at ambient temperature and essentially zero power and continues throughout the power spike. The system kinetic energy is seen also significant in this case at rates above \$10/sec (approximately 2×10^{20} fissions). For insertion rates below ~\$10/sec (not plotted), the fission release is approximately proportional to the one-half power of the rate.

Figures A-9 through A-11 apply specifically to the control vane "run-out" accident. Figures A-9 depicts the spike powers versus time for the three rotational speeds discussed in Section VI-B; Figure A-10, the integrated power or total fission release for each of these cases as a function of time; Figure A-11, the reactivity insertion (dollars over delayed critical) versus time for these cases. For these latter cases, the RTS code was employed with a delayed neutron fraction of 0.0073, a neutron lifetime of 25 μsec (in lieu of the computed value of 30 μsec), and a prompt negative temperature coefficient of \$1.20/1000°C. The calculated spike power levels and total energy releases, however, have been corrected for an assumed B-4 coefficient of \$0.75/1000°C, and these are the data plotted in Figures A-9 and A-10.

Figure A-7
NERVA B-4 Spike Power Versus Reactivity Insertion [129]

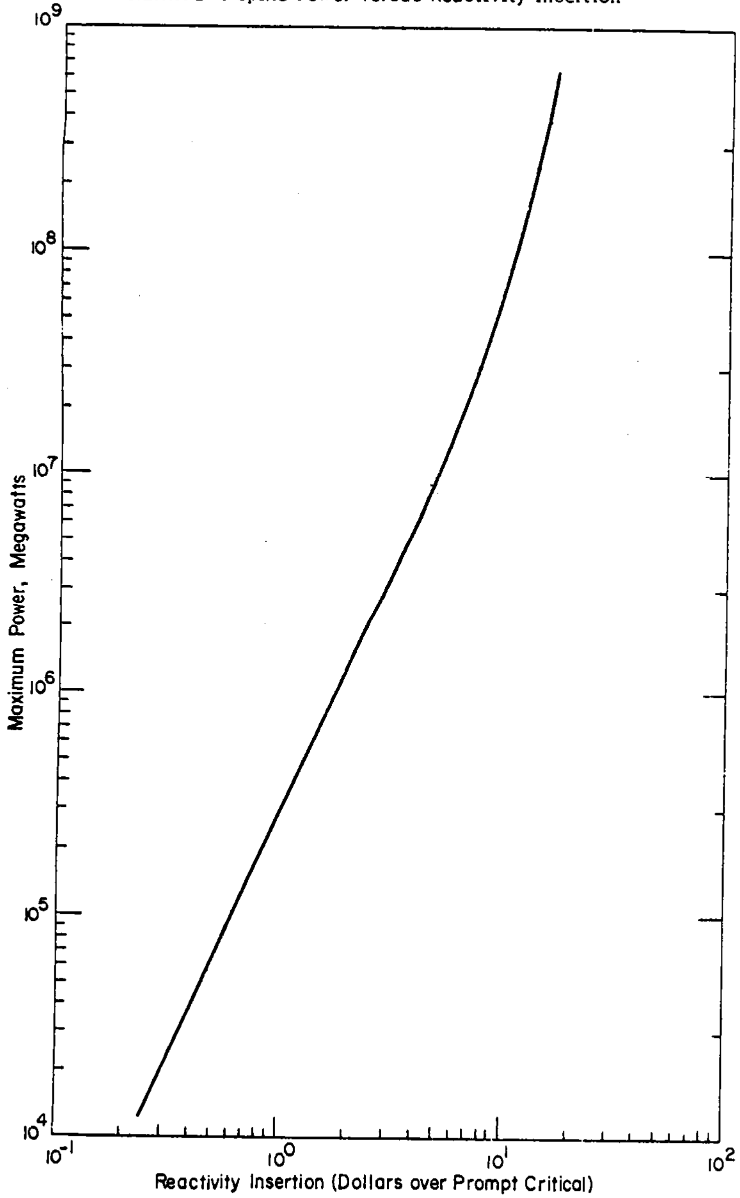


Figure A-8
NERVA B-4 Energy Release Versus Reactivity Insertion Rate [128]

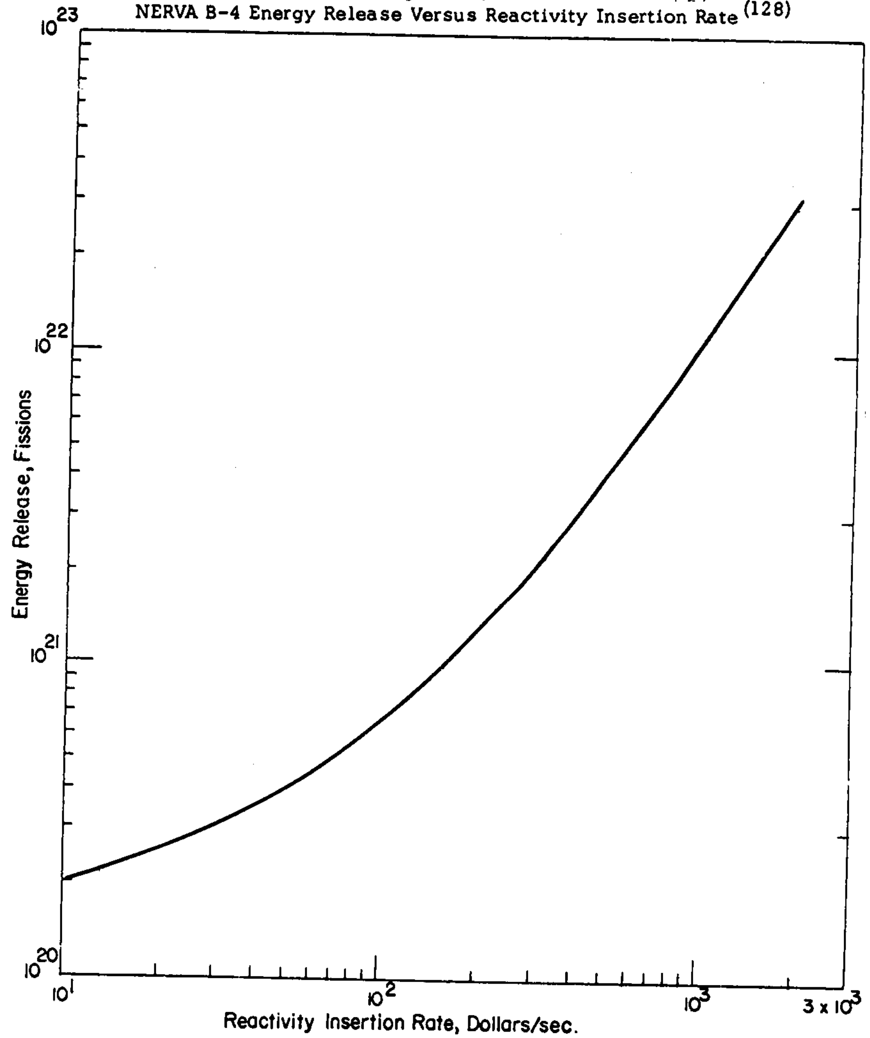


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Figure A-9
NERVA B-4 Control Vane Spike Power Versus Time (130)

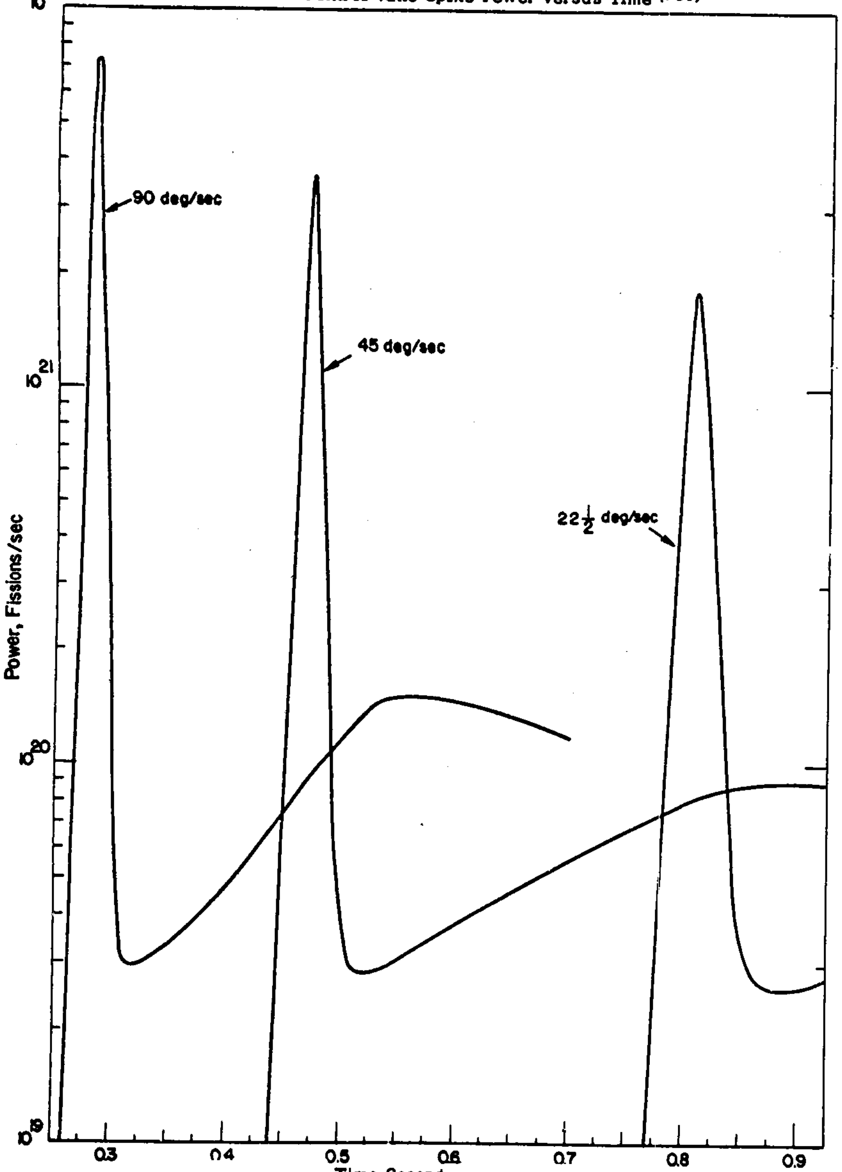


Figure A-10
NERVA B-4 Control Vane Energy Release Versus Time (130)

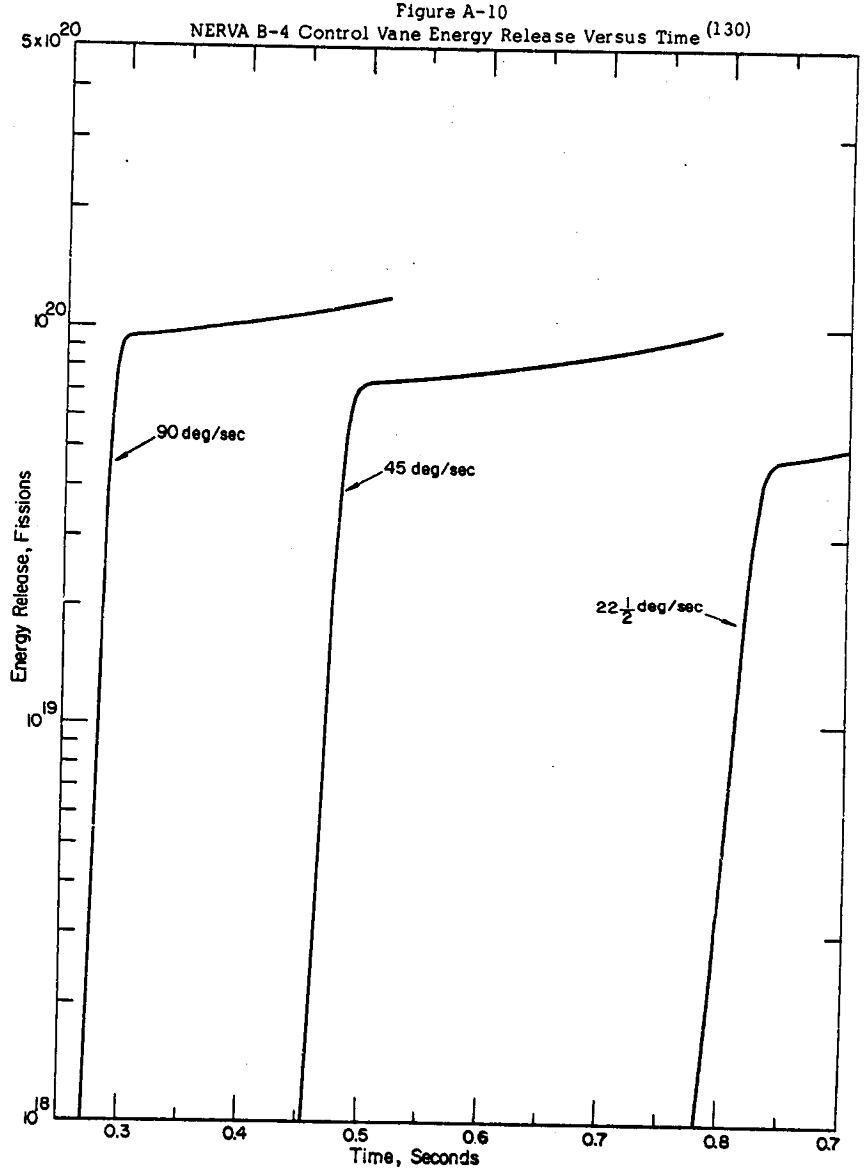
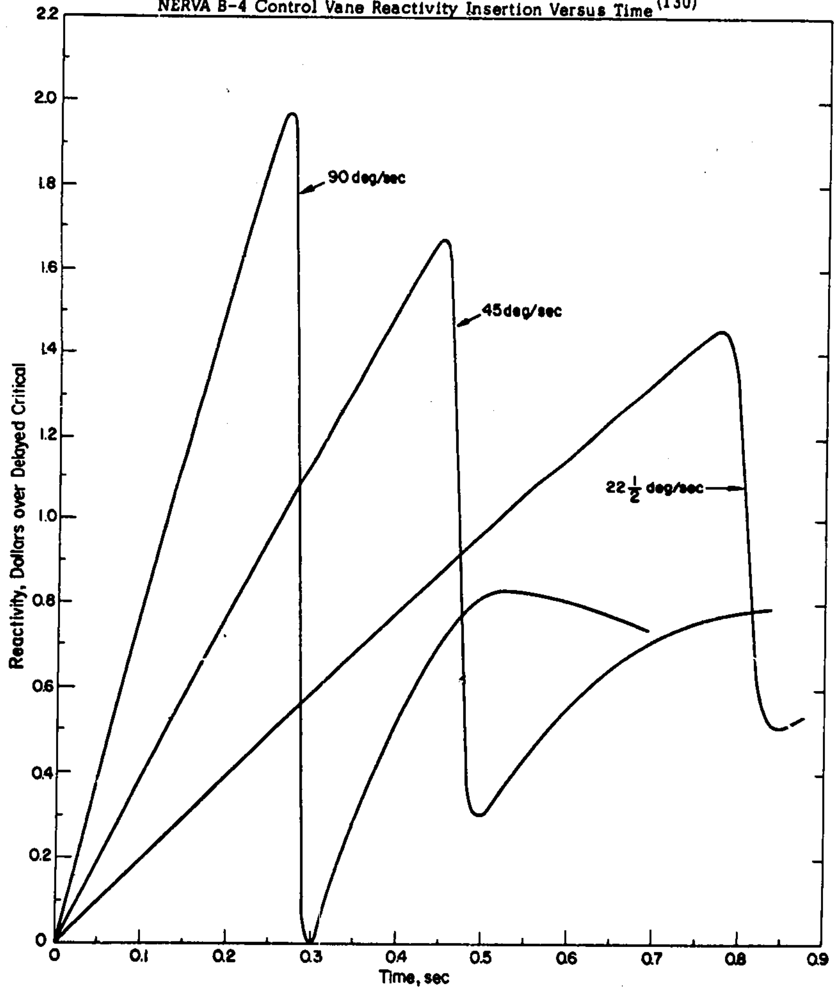


Figure A-11

NERVA B-4 Control Vane Reactivity Insertion Versus Time (130)



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